Engineer On a Disk

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1. TABLE OF CONTENTS

Reference Information

2. BASIC MANUFACTURING

• Manufacturing is an ages old topic, spanning the entire history of modern man.

• There are some recurring themes in mans manufacturing techniques.
  - cutting
  - grinding
  - drilling

• The basic manufacturing processes generally work one material mechanically with another material.

• There are some basic factors that can be boiled out of the cutting factors. Primarily, cutting forces will be examined, along with the economics of basic machining.

2.1 INTRODUCTION

• Why are new manufacturing processes being developed?
  - new materials that are not suitable to traditional machining methods.
  - new approaches to design and manufacture
  - more complicated designs
  - tighter tolerances

• The basic characteristic of any process is some form of energy and/or mass transfer to alter the physical form and properties of an object.

• In general, topics to be covered are varied, but overall they tend to complement various weaknesses in the older machining and forming technologies.

• The process specific topics to be covered are,

Cutting - separating materials is done by physically breaking bonds, or more recently by melting. Cutting techniques have found particular favor with sheets of material, such as metal plates, metal sheets, fabrics, etc.

Metallurgical/Finishing - a variety of processes that do not significantly alter the geometry of the object, but are required for product performance or marketing. Consider heat treating processes that will heat a metal and change the properties. Or painting that makes a part more attractive and helps protect the metal surface.

Molding/Casting - Molding and casting technologies have been used for millennia, but they have recently begun to find interesting new techniques, and materials that expand the applications, and techniques. In general this method uses material in a liquid form, that solidifies into the shape of a mold.

Particulates - small particles of material have been used to manufacture low cost parts of complex geometry at high production rates. In effect a powder is put in a mold, pressed until solid, then heated to make it stronger. Materials include many metals, ceramics, glass, etc.

Forming - The idea of reshaping objects has been done for long periods of time (e.g. blacksmiths). Our knowledge of materials has allowed us to take advantage of subtle properties. Certain materials can be worked past the point that they would normally fracture. Materials can be bonded at an atomic level, and entire parts can be made out of a single crystal.

Joining/Cutting - By joining two or more parts we can create more complex geometries and assemblies. Consider parts that are glued or welded together. Parts may also be made by cutting larger parts into smaller pieces.

Electrical/Chemical - The transformational abilities of electricity have long been known (e.g. lightning), but it has only been controllable in the last two centuries. The ability to manipulate energy at the atomic level allows us to deliver highly concentrated energy, or manipulate materials one atom at a time. Most of these techniques use electrical potential, or flows to move, manipulate, and heat materials.

Fibre - By mixing two materials at a macroscopic level, we can obtain properties that are not possible from common materials. This technique basically involves taking strong strands of one materials, and embedding it in another material. Good examples of these materials are boat hulls, rocket fuel tanks and nozzles, fibre reinforced tape.

Rapid Prototyping - A newly recognized need is to turn out parts of correct geometry, and reasonable solid properties for testing of new designs, and sometimes production of tooling. These techniques typically make parts in layers, and allow complex new geometries to be built. The layers are often built with photopolymers that are developed with laser light.

• Various ways to look at processes include,
  - stress - strain curves
  - metal alloy phase diagrams
  - fluid flow problems
  - etc.

2.2 PRACTICE PROBLEMS

1. List 10 different manufacturing processes you have seen or used. Divide these into major categories of manufacturing processes.

2. Review the process tree in the textbook, count the number of processes you recognize.

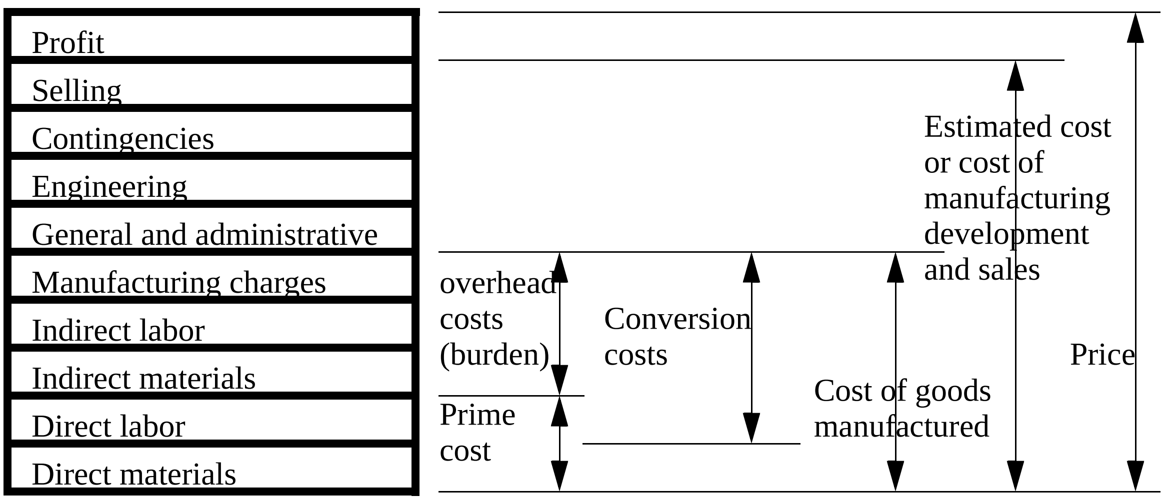
3. MANUFACTURING COST ESTIMATING

3.1 COSTS ESTIMATES

• Cost estimating attempts to estimate to estimate the value put into a product by each operation.

• Cost estimates are based on historical records of expenses for equipment.

• Costs are made up of a variety of components,



• Estimated variables for a single product/unit. NOTE: yearly estimates are typically made by management.

$$C_{P_{job}}, C_{P_{year}} = \text{ profit}$$
$$C_{S_{job}}, C_{S_{year}} = \text{ sales costs (this can be as much as 50\% in some industries)}$$
$$C_{C_{job}}, C_{C_{year}} = \text{ contingincies (e.g., insurance)}$$
$$C_{E_{job}}, C_{E_{year}} = \text{ engineering costs (salaries, computers, etc)}$$
$$C_{A_{job}}, C_{A_{year}} = \text{ administration (executive salaries)}$$
$$C_{MO_{job}}, C_{MO_{year}} = \text{ manufacturing overhead charges}$$
$$C_{IL_{job}}, C_{IL_{year}} = \text{ indirect labor}$$
$$C_{IM_{job}}, C_{IM_{year}} = \text{ indirect materials}$$
$$C_{DL_{job}}, C_{DL_{year}} = \text{ direct labor}$$
$$C_{DM_{job}}, C_{DM_{year}} = \text{ direct materials}$$
$$OH_{job} = \text{ overhead costs}$$
$$PC_{job} = \text{ prime costs}$$
$$CC_{job} = \text{ conversion costs}$$
$$COGM_{job} = \text{ cost of goods manufactured}$$
$$P_{job} = \text{ selling price}$$
$$EC_{job} = \text{ estimated cost}$$

• We can write equations for the simple relationships,

$$OH_{job} = C_{IL_{job}} + C_{IM_{job}} + C_{MO_{job}}$$
$$PC_{job} = C_{DM_{job}} + C_{DL_{job}}$$
$$COGM_{job} = PC_{job} + OH_{job}$$
$$CC_{job} = COGM_{job} - C_{DM_{job}}$$
$$EC_{job} = COGM_{job} + C_{A_{job}} + C_{E_{job}} + C_{C_{job}} + C_{S_{job}}$$
$$P_{job} = EC_{job} + C_{P_{job}}$$

• We can select a profit using market conditions,

$$C_{P_{job}} = \left(\frac{1}{100}\right) EC_{job}$$ very high competition / low risk

$$C_{P_{job}} = \left(\frac{10}{100}\right) EC_{job}$$ low competition

$$C_{P_{job}} = \left(\frac{20}{100}\right) EC_{job}$$ has market cornered

• We need to estimate the total time for the job using the process plan.

$$T_{OPERATION_i} = \text{ the estimated time for operation i}$$

$$T_{job} = \sum T_{OPERATION_i}$$

• We can then include time to find the various costs. There are many ways to do this - this is one possible way.

$$T_{year} = \text{ total productive machine hours in a year (estimated)}$$

$$C_{S_{job}} = C_{S_{year}}\left(\frac{T_{job}}{T_{year}}\right)$$

$$C_{C_{job}} = C_{C_{year}}\left(\frac{T_{job}}{T_{year}}\right)$$

$$C_{E_{job}} = C_{E_{year}}\left(\frac{T_{job}}{T_{year}}\right)$$

$$C_{A_{job}} = C_{A_{year}}\left(\frac{T_{job}}{T_{year}}\right)$$

Note: When jobs are unique and require more/less cost than average, these rates can and should be adjusted. Avoid mis-estimating as this will lead to economic losses or lost bids.

• Some costs must be specific to materials used. Depending upon suppliers, shipping, handling, etc. these costs will vary widely. If we use a fairly consistent supplier we can use,

$$C_{IM_{job}} = \left(\frac{C_{DM_{job}}}{C_{DM_{year}}}\right) C_{IM_{year}}$$

• We can estimate indirect labor costs using an assumption that most labor types are fairly similar (this is not true but other book keeping problems may encourage this).

$$C_{IL_{job}} = C_{IL_{year}}\left(\frac{C_{DL_{job}}}{C_{DL_{year}}}\right)$$

• For continuous-long running jobs (minimal setups) using the process plan time estimates we are already to estimate the direct labor costs.

$$PHC_{OPERATION_i} = \text{ productive hour costs (found in AMCE section II)}$$

$$C_{DL_{job}} = \sum T_{OPERATION_i} PHC_{OPERATION_i}$$

• We can estimate direct material costs two ways using the process plan, the AMCE, and quotes from suppliers.

$$W_F = \text{ weight of finished part}$$

$$L_1 = \text{ \% losses due to scrap (rejects)}$$

$$L_2 = \text{ \% losses due to waste (chips, cutting, runners)}$$

$$L_3 = \text{ \% inventory losses (theft/spoilage/shrinkage)}$$

$$C_{material} = \text{ material costs per unit weight}$$

$$C_{DM} = C_{material} W_F (1 + L_1 + L_2 + L_3)$$

OR

$$W_{stock_i} = \text{ weight of required stock i}$$

$$C_{stock_i} = \text{ cost per unit stock i}$$

$$C_{DM} = \frac{\sum (W_{stock_i} C_{stock_i})}{(1 - L_1 - L_2)}$$

Note: these equations will have to be reconsidered as various manufacturing processes are used. For example, reground plastic. Reworking costs, inventory costs, scrap dealer pays for cuttings, volume discounts, etc.

• Jobs may run in small batches and require setups and multiple steps on a machine. We can do a more detailed cost estimate based on operation steps (using section 5 in the AMCE).

$$n = \text{\# of parts in batches}$$

$$C_{operation_i} = \text{operation costs calculated using equations in AMCE sec.5}$$

$$C_{DL_{job}} = \sum C_{operation_i}\left(\frac{n}{100}\right)$$

> Note: these costs are typically given for batches of 100, we can correct using a simple correction. We could also include scrap, etc.

• If operations at a machine contain multiple steps we can develop a more detailed estimate using the information in section 5 of the AMCE. To do this we need to break each operation down to specific steps. Detail is critical with this method.

$$j = \text{operation j is a sub-step of operation i}$$

$$T_{operation_i} = \left(\frac{T_{setup_{operation_i}}}{n} + \sum T_{step_j}\right)$$

• We can use a tabular format (based on a process plan) to calculate,

part # ____________________
part name ____________________
plant ____________________

quantity ________
material ____________
material cost ________

Op #	machine/ station	data source	operation description	setup time	operation time	lot time	hourly cost	lot cost

• Consider the example below,

******************* find a financial statement

************************** find a simple part design

3.2 COGS (COST OF GOODS SOLD)

• This is a tax deduction for a business

COGS = INVENTORY AVAILABLE - FINAL INVENTORY
= INITIAL INVENTORY + PURCHASES

3.3 VALUE ENGINEERING

• We can compare the economic cost of a design feature to the economic value assigned it by the customer.

$$V_{feature} = \frac{V_{consumer}}{V_{\cos t}}$$

• This simple measure allows us to rate features in a part and identify candidates for redesign.

3.4 REFERENCES

Ostwald, P.F., American Machinist Cost Estimator, McGraw-Hill, 1985.

Ullman, D.G., The Mechanical Design Process, McGraw-Hill, 1997.

4. BASIC CUTTING TOOLS

4.1 CUTTING SPEEDS, FEEDS, TOOLS AND TIMES

• Cutting is a balance between a number of factors,
  - cutting slowly will add costly time to manufacturing operations.
  - cutting faster will lead to decreased tool life, and extra time will be required to repair tools.

• Some reasonable speeds and feeds for a single cutting point tool are given below [Krar],

MATERIAL	DEPTH (in.)	FEED PER REV. (ipr)	CUTTING SPEED (fpm)
Aluminum	0.005-0.015	0.002-0.005	700-1000
	0.020-0.090	0.005-0.015	450-700
	0.100-0.200	0.015-0.030	300-450
	0.300-0.700	0.030-0.090	100-200
Brass, Bronze	0.005-0.015	0.002-0.005	700-800
	0.020-0.090	0.005-0.015	600-700
	0.100-0.200	0.015-0.030	500-600
	0.300-0.700	0.030-0.090	200-400
cast iron (medium)	0.005-0.015	0.002-0.005	350-450
	0.020-0.090	0.005-0.015	250-350
	0.100-0.200	0.015-0.030	200-250
	0.300-0.700	0.030-0.090	75-150
machine steel	0.005-0.015	0.002-0.005	700-1000
	0.020-0.090	0.005-0.015	550-700
	0.100-0.200	0.015-0.030	400-550
	0.300-0.700	0.030-0.090	150-300
tool steel	0.005-0.015	0.002-0.005	500-750
	0.020-0.090	0.005-0.015	400-500
	0.100-0.200	0.015-0.030	300-400
	0.300-0.700	0.030-0.090	100-300
stainless steel	0.005-0.015	0.002-0.005	375-500
	0.020-0.090	0.005-0.015	300-375
	0.100-0.200	0.015-0.030	250-300
	0.300-0.700	0.030-0.090	75-175
titanium alloys	0.005-0.015	0.002-0.005	300-400
	0.020-0.090	0.005-0.015	200-300
	0.100-0.200	0.015-0.030	175-200
	0.300-0.700	0.030-0.090	50-125

4.2 HIGH SPEED MACHINING

• Usually spindle speeds above 10000 RPM, but this is highly relative to the cutting tool and work.

• The cutting velocity is higher, but the feed/depth of the cut is reduced, the resulting mrr is still higher.

• Higher spindle speeds call for new low inertia spindle, and tolerances as well. Small tolerance problems can result in unacceptable vibrations at these speeds.

• The table below is an example of some cutting speeds [Ashley, 1995]

	Solid tools - end mills, drills WC, coated WC, PCD, ceramic		Indexable tools - shell and face mills WC, ceramic, sialon, CBN, PCD	
Work material	Typical velocity (fpm)	High Speed (fpm)	Typical velocity (fpm)	High Speed (fpm)
aluminum	1000+ (WC,PCD)	10000+ (WC,PCD)	2000+	12000+ (WC,PCD)
cast iron soft ductile	 500 350	 1200 800	 1200 800	 4000(sia.,cer.) 3000(cer.)
steel free machining steel alloy stainless hardness RC65	 350 250 350 80	 1200 800 500 400	 1200 700 500 100(WC) 300(CBN,cer.)	 2000 1200 900 150(WC) 600(CBN,cer.)
titanium	125	200	150	300
superalloy (Iconel)	150	250	275(WC) 700(sia.)	1200(sia.,cer.)

4.3 REFERENCES

Ashley, S., “High Speed Machining Goes Mainstream”, Mechanical Engineering, published by the ASME, May 1995, pp. 56-61.

5. CUTTING THEORY

• When we cut metal, the severed pieces are cast off, these are referred to as chips.

5.1 CHIP FORMATION

• There are three types of chips that are commonly produced in cutting,
  - discontinuous chips
  - continuous chips
  - continuous with built up edge

• A discontinuous chip comes off as small chunks or particles. When we get this chip it may indicate,
  - brittle work material
  - small rake angles
  - coarse feeds and low speeds

• A continuous chip looks like a long ribbon with a smooth shining surface. This chip type may indicate,
  - ductile work materials
  - large rake angles
  - fine feeds and high speeds
  - use of coolant and good chip flow

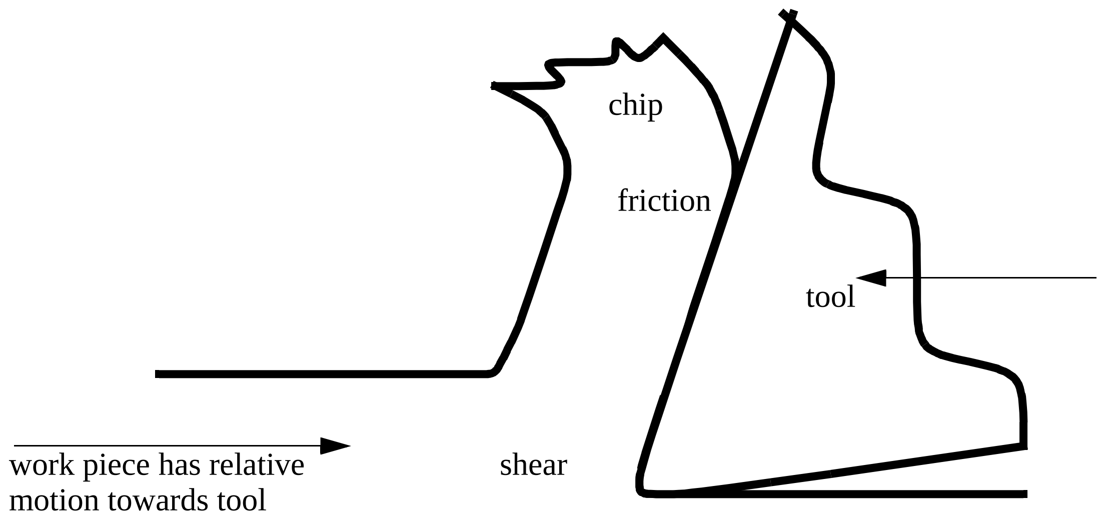
• Continuous chips with a built up edge still look like a long ribbon, but the surface is no longer smooth and shining. This type of chip tends to indicate,
  - high friction between work and tool causes high temperatures that will occasionally weld the chip to the tool. This will break free, but the effects is a rough cutting action.

• Continuous chips, and subsequently continuous cutting action is generally desired.

5.2 THE MECHANISM OF CUTTING

• Assuming that the cutting action is continuous we can develop a continuous model of cutting conditions.

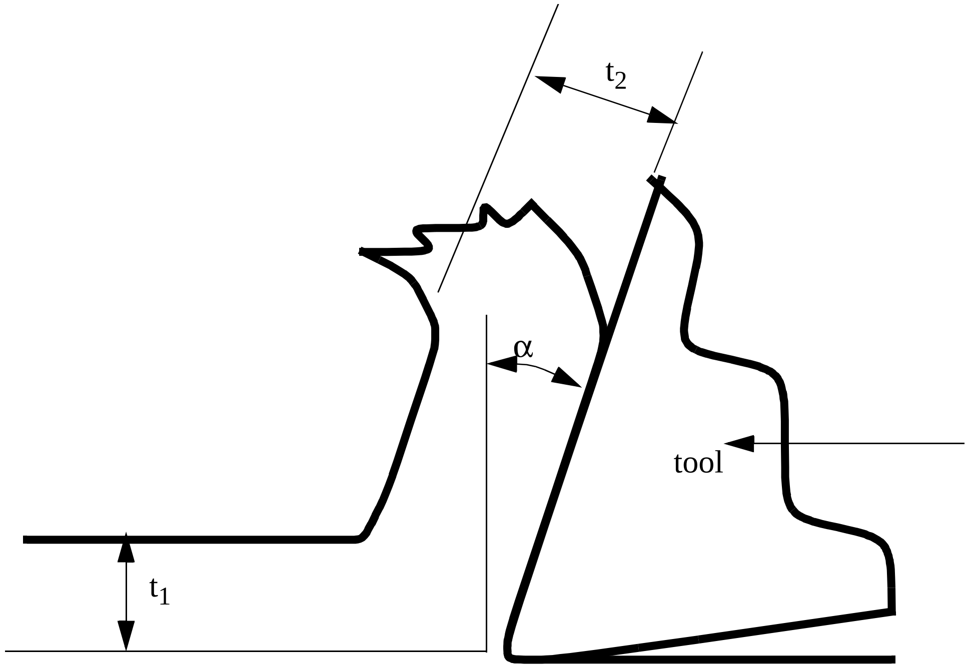
• Orthogonal Cutting - assumes that the cutting edge of the tool is set in a position that is perpendicular to the direction of relative work or tool motion. This allows us to deal with forces that act only in one plane.



• We can obtain orthogonal cutting by turning a thin walled tube, and setting the lath bit cutting edge perpendicular to the tube axis.

• Next, we can begin to consider cutting forces, chip thicknesses, etc.

• First, consider the physical geometry of cutting,

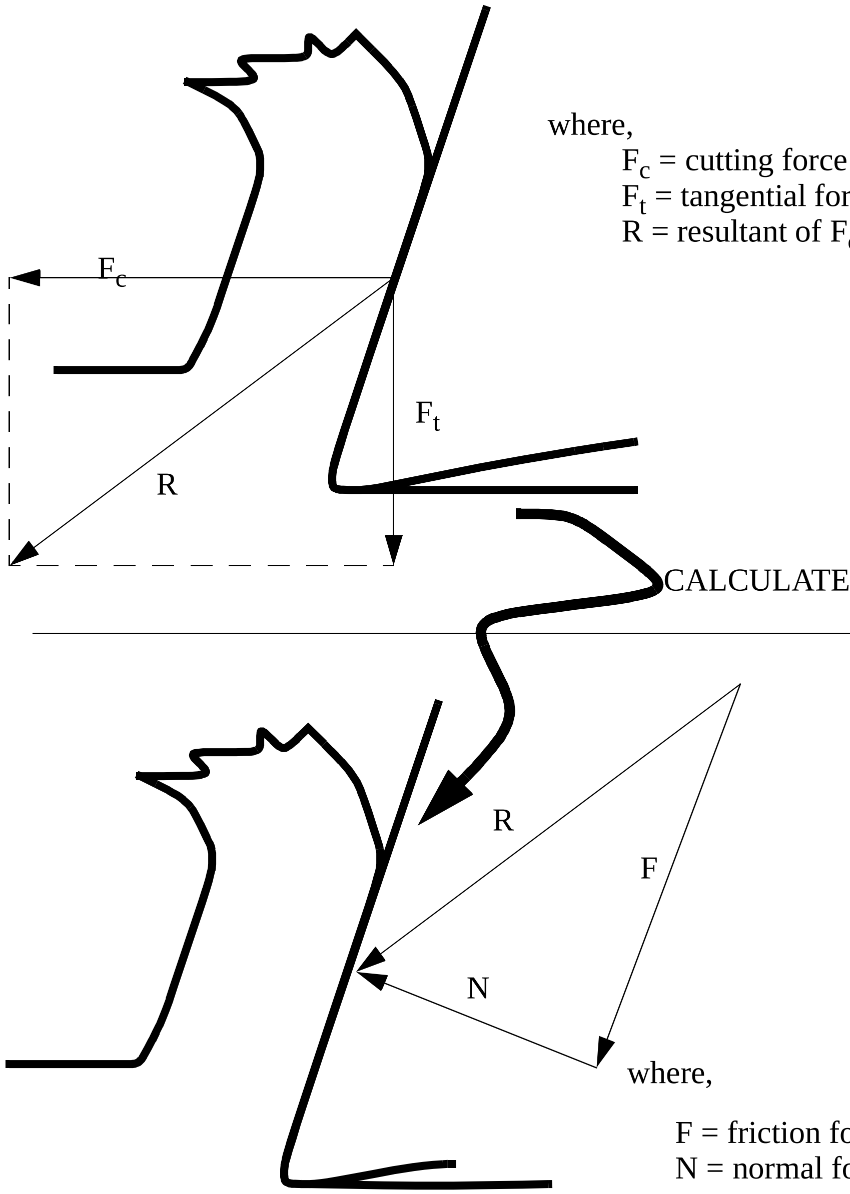


where,

t_1 = undeformed chip thickness
t_2 = deformed chip thickness (usually $t_2 > t_1$)
α = tool rake angle

If we are using a lathe, t_1 is the feed per revolution

- Next, we assume that we are also measuring two perpendicular cutting forces that are horizontal, and perpendicular to the figure above. This then allows us to examine specific forces involved with the cutting. The cutting forces in the figure below (Fc and Ft) are measured using a tool force dynamometer mounted on the lathe.



where,

F_c = cutting force (measured)
F_t = tangential force (measure)
R = resultant of F_c and F_t

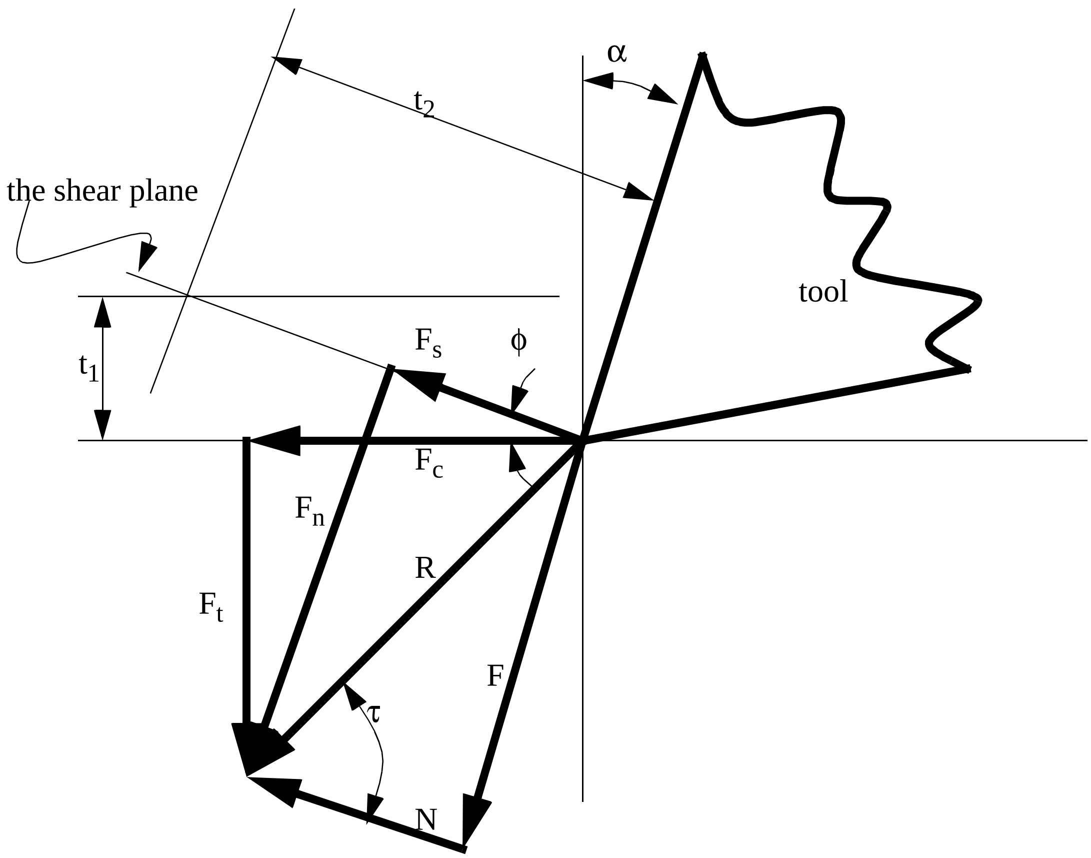
where,

F = friction force between tool and chip
N = normal force between tool and chip

5.2.1 Force Calculations

5.2.1.1 - Force Calculations

• The forces and angles involved in cutting are drawn below,



F_s = shear force
F_n = force normal to shear plane
α = tool rake angle (positive as shown)
φ = shear angle
τ = friction angle

- Having seen the vector based determination of the cutting forces, we can now look at equivalent calculations

$$\frac{F}{N} = \tan\tau = \mu$$

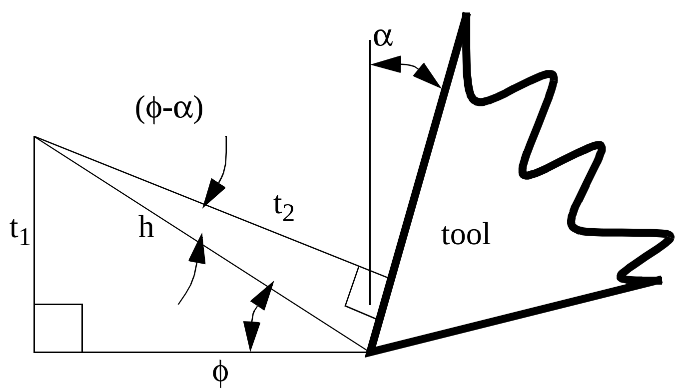
where,

μ = the coefficient of friction

$$\boxed{r_c = \frac{t_1}{t_2}}$$

where,

r_c = the cutting ratio



$$t_1 = h\sin\phi \qquad t_2 = h\cos(\phi - \alpha)$$

$$r_c = \frac{t_1}{t_2} = \frac{h\sin\phi}{h\cos(\phi-\alpha)} = \frac{\sin\phi}{\cos\phi\cos\alpha + \sin\phi\sin\alpha}$$

$$\therefore r_c\cos\phi\cos\alpha + r_c\sin\phi\sin\alpha = \sin\phi$$

$$\therefore \frac{r_c\cos\phi\cos\alpha}{\sin\phi} + \frac{r_c\sin\phi\sin\alpha}{\sin\phi} = 1$$

$$\therefore \frac{r_c\cos\alpha}{\tan\phi} = 1 - r_c\sin\alpha$$

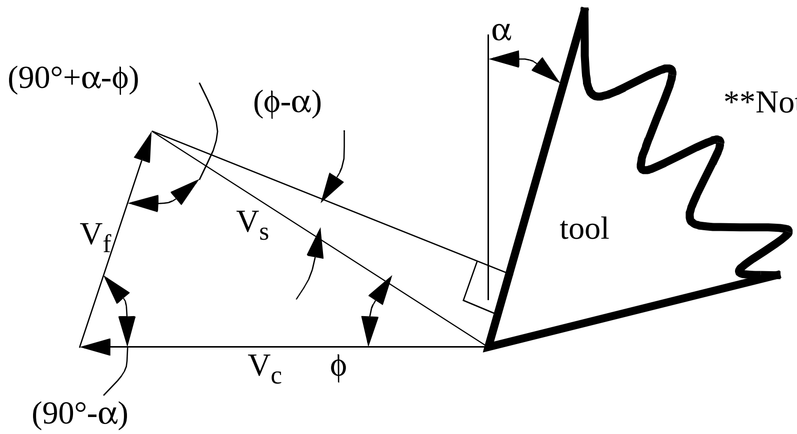
$$\boxed{\therefore \tan\phi = \frac{r_c\cos\alpha}{1 - r_c\sin\alpha}}$$

And, by trigonometry,

$$\boxed{F = F_t \cos\alpha + F_c \sin\alpha \qquad\qquad F_s = F_c \cos\phi - F_t \sin\phi}$$

$$N = F_c \cos\alpha - F_t \sin\alpha \qquad\qquad F_n = F_c \sin\phi + F_t \cos\phi$$

• The velocities are also important, and can be calculated for later use in power calculations. The Velocity diagram below can also be drawn to find cutting velocities.



**Note: graphical solutions are possible

where,

V_c = cutting velocity (ft./min.) - as set or measured on the machine
V_s = shearing velocity
V_f = frictional velocity

Using the sine rule,

$$\frac{V_s}{\sin(90° - \alpha)} = \frac{V_c}{\sin(90° + \alpha - \phi)}$$

$$\boxed{\therefore V_s = \frac{V_c \sin(90° - \alpha)}{\sin(90° + \alpha - \phi)} = \frac{V_c \cos\alpha}{\cos(\phi - \alpha)}}$$

Also,

$$\boxed{V_f = \frac{V_c \sin\phi}{\cos(\phi - \alpha)}}$$

• A final note of interest to readers not completely familiar with vectors, the forces F_c and F_t, are used to find R, from that two other sets of equivalent forces are found.,

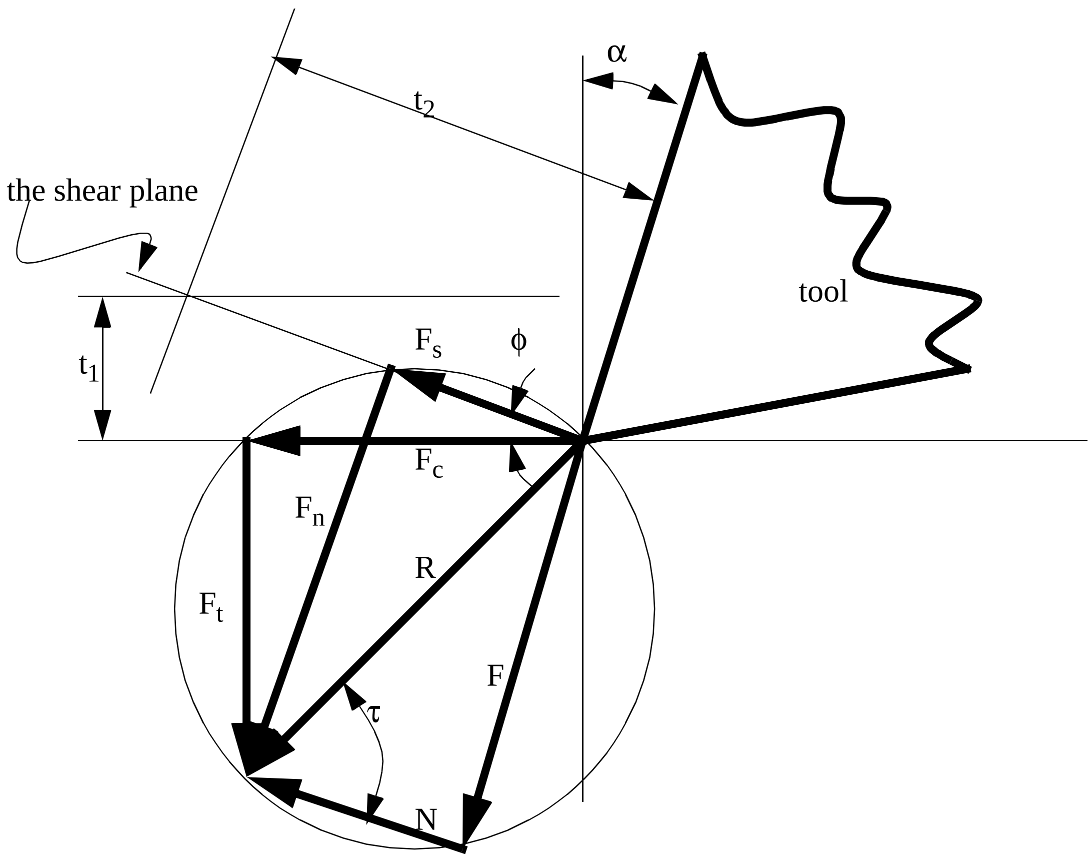
$$R = \sqrt{F_c^2 + F_t^2} = \sqrt{F_s^2 + F_n^2} = \sqrt{F^2 + N^2}$$

5.2.1.2 - Merchant's Force Circle With Drafting (Optional)

- Merchant's Force Circle is a method for calculating the various forces involved in the cutting process. This will first be explained with vector diagrams, these in turn will be followed by a few formulas.

- The procedure to construct a merchants force circle diagram (using drafting techniques/instruments) is,
    1. Set up x-y axis labeled with forces, and the origin in the centre of the page. The scale should be enough to include both the measured forces. The cutting force (F_c) is drawn horizontally, and the tangential force (F_t) is drawn vertically. (These forces will all be in the lower left hand quadrant) (Note: square graph paper and equal x & y scales are essential)
    2. Draw in the resultant (R) of F_c and F_t.
    3. Locate the centre of R, and draw a circle that encloses vector R. If done correctly, the heads and tails of all 3 vectors will lie on this circle.
    4. Draw in the cutting tool in the upper right hand quadrant, taking care to draw the correct rake angle (α) from the vertical axis.
    5. Extend the line that is the cutting face of the tool (at the same rake angle) through the circle. This now gives the friction vector (F).
    6. A line can now be drawn from the head of the friction vector, to the head of the resultant vector (R). This gives the normal vector (N). Also add a friction angle (τ) between vectors R and N. As a side note recall that any vector can be broken down into components. Therefore, mathematically, $R = F_c + F_t = F + N$.
    7. We next use the chip thickness, compared to the cut depth to find the shear force. To do this, the chip is drawn on before and after cut. Before drawing, select some magnification factor (e.g., 200 times) to multiply both values by. Draw a feed thickness line (t_1) parallel to the horizontal axis. Next draw a chip thickness line parallel to the tool cutting face.
    8. Draw a vector from the origin (tool point) towards the intersection of the two chip lines, stopping at the circle. The result will be a shear force vector (F_s). Also measure the shear force angle between F_s and F_c.
    9. Finally add the shear force normal (F_n) from the head of F_s to the head of R.
    10. Use a scale and protractor to measure off all distances (forces) and angles.

- The resulting diagram is pictured below,



F_s = shear force
F_n = force normal to shear plane
α = tool rake angle (positive as shown)
ϕ = shear angle
τ = friction angle

5.3 POWER CONSUMED IN CUTTING

• There are a number of reasons for wanting to calculate the power consumed in cutting. These numbers can tell us how fast we can cut, or how large the motor on a machine must be.

• Having both the forces and velocities found with the Merchant for Circle, we are able to calculate the power,

$$P_c = \frac{F_c V_c}{33000}$$

$$P_s = \frac{F_s V_s}{33000}$$

$$P_f = \frac{F \times V_f}{33000}$$

All have units of Horsepower (i.e., 1/33000)

where,

P_c = the total cutting power
P_s = the shearing power required
P_f = the friction losses

• We can relate the energy used in cutting to the mrr.

Energy Consumed $P_c = F_c \times V_c$

Metal Removal Rate $Q = A_0 \times V_c$

where,

A_0 = Area of Cut

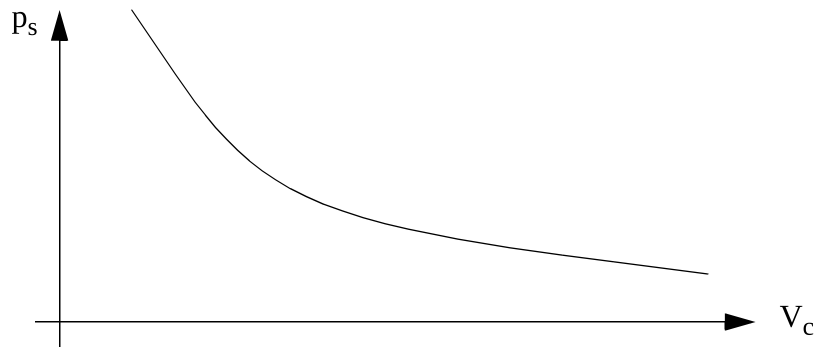
***Note: both W_c and Q are proportional to V_c

From these basic relationships we can a simple relationship that is the ratio between the energy consumed, and the volume of metal removed,

$$p_s = \frac{P_c}{Q} = \frac{F_c \times V_c}{A_0 \times V_c} = \frac{F_c}{A_0}$$

You will notice that the result is a force over an area, which is a pressure. As a result P_s will be called the Specific Cutting Pressure.

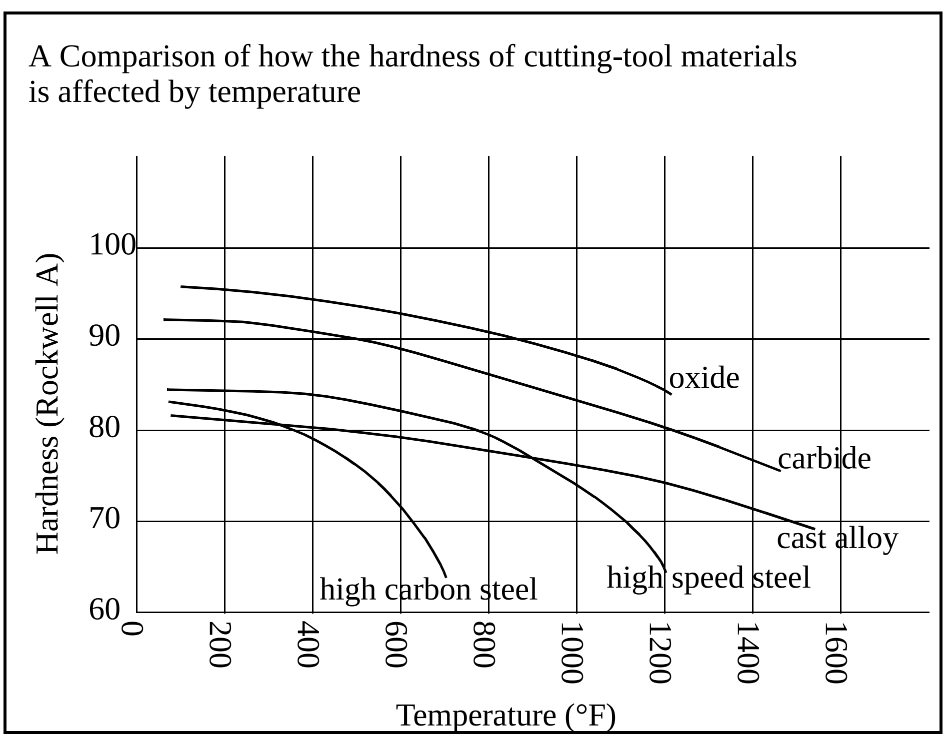
• The cutting force will vary, thus changing P_s, as the cutting velocities are changed.



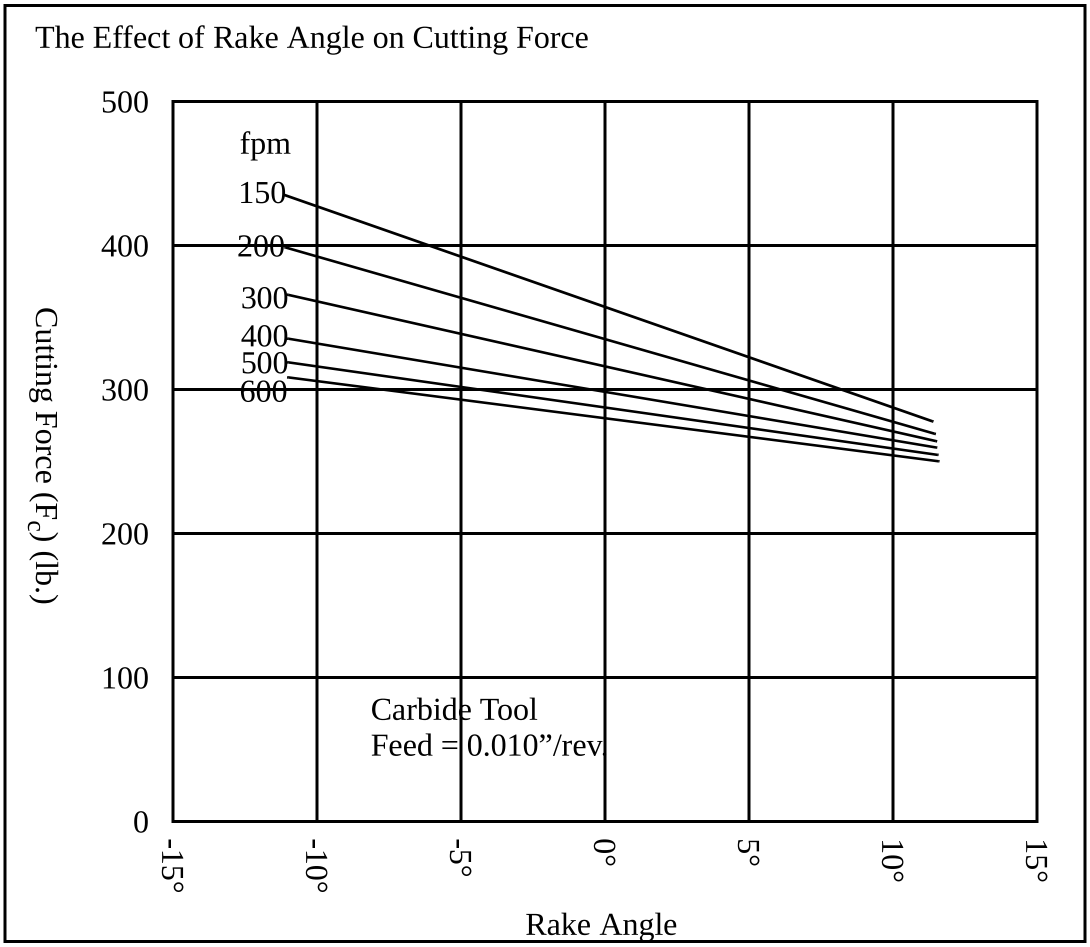
This curve turns downward for two reasons,

1. The tool experiences edge forces that are more significant at lower cutting speeds.
2. As the velocity increases, the temperature increases, and less energy is required to shear the metal.

• Tool hardness is degraded by temperature, as shown in the diagram below [REF]



• The effects of rake angle on cutting are shown in the graph below, [REF ******]



• The horsepower required for cutting can be found using empirical methods, Unit horse power (HP_u) is the amount of power to remove a volume of metal in a period of time.

$$HP_u = \text{power to cut 1 cubic inch per minute - found in tables}$$

$$HP_g = Q \times HP_u = \text{Gross Horsepower}$$

Average Unit Horsepower Values of Energy Per Unit Volume [REF]

Material	BHN	HP_u (HP/(in^3/min.)
Carbon steels	150-200	1.0
	200-250	1.4
	250-350	1.6
Leaded steels	150-175	0.7
Cast irons	125-190	0.5
	190-250	1.6
Stainless steels	135-275	1.5
Aluminum alloys	50-100	0.3
Magnesium alloys	40-90	0.2
Copper	125-140	0.7
Copper alloys	100-150	0.7

- If we consider the implications these formulas have when cutting on a lathe, we would be able to develop the following equations,

$$Q = f \times d \times V \times 12$$

where,

f = feed
d = depth or cut
V = velocity

$$HP_c = \frac{F_c \times V_c}{33000} = HP_u \times Q \times c$$

where,

c = a feed factor from tables

Horsepower Feed Correction Factors for Turning, Planning and Shaping [RE

Feed		Factor
(ips or ipr)	(mm/rev or mm/stroke)	
0.002	0.05	1.4
0.005	0.12	1.2
0.008	0.20	1.05
0.012	0.30	1.0
0.020	0.50	0.9
0.030	0.75	0.80
0.040	1.00	0.80
0.050	1.25	0.75

We can also consider the efficiency of the machine tool,

$$HP_g = \frac{HP_c}{e_m}$$

where,

e_m = the machine tool efficiency factor [0,1]

from this we can determine the minimum machine tool horsepower required,

$$HP_M = HP_I + HP_g = HP_I + \frac{HP_c}{e_m}$$

where,

HP_M = The minimum machine tool horse power required

HP_I = The idle horsepower consumed by the machine tool

5.4 PRACTICE QUESTIONS

1. An orthogonal cut is made with a carbide tool having a 15° positive rake angle. The various parameters were noted,
   - the cut width was 0.25”
   - the feed was set at 0.0125”
   - the chip thickness was measured to be 0.0375”
   - the cutting speed was 250 ft./min.
   - the forces measured were F_c = 375 lb. and F_t = 125 lb.

   a) Use Merchant’s Circle to scale, and the velocity diagram
   b) From the Merchant Circle diagram find the shear angle (ϕ), friction force (F), friction normal force (N), and shear force (F_s).
   c) From theVelocity diagram find the friction velocity (V_f).
   d) Calculate values for the coefficient of friction (mu) and the metal removal rate.
   e) Calculate values, and compare the results for the results found in a), b) and c).

(ans: F = 218lb., N = 330lb., ϕ= 19.37°, F_s = 312 lb., μ= 0.948, V_c = 250 ft./min., V_f = 83.5 ft./min. Q = 9.375 in^3/min.)

2. The cutting forces for a lathe are listed below,
   • work RPM = 125

- feed/rev = 0.005”
- chip thickness = 0.0123”
- rake angle of tool = 14°
- Ft = 150 lb, Fc = 245 lb
- work diameter = 8”

a) Find the horsepower consumed in cutting, shearing and friction.
b) Find a maximum lathe horsepower, assuming the machine efficiency is 95% and it requires 1/8 idle horsepower.
c) Based on the cutting horsepower, what material(s) might we be cutting?

3. What roles do rake and relief angles play in cutting tools?

ans. the rake angle will change the basic cutting parameters. A positive rake (sharp tool) will give lower cutting forces, but less edge strength. A negative or neutral rake will give higher cutting forces, but more strength. The relief angle provide a gap behind the cutting edge so that the tool does not rub the work.

4. Which of these statement is the most correct?
   a) a continuous chip with built up edge may result when we try to cut too much metal.
   b) a continuous chip will result when cutting very brittle work materials.
   c) a discontinuous chip will result when we use fine feeds and speeds.
   d) none of the above.

ans. a

5. One of the assumptions behind orthogonal cutting is,
   a) that the rake angle is positive.
   b) that the tool is only cutting with one edge and one point.
   c) the shear plane is a function of before and after chip thicknesses.
   d) none of the above.

ans. b

6. Which of these statements is correct?
   a) the cutting pressure drops as cutting velocity increases.
   b) power required drops as metal temperature and cutting velocity increase.
   c) we can use the quantity of metal removed by itself to estimate the required horsepower of a machine tool.
   d) all of the above.

ans. a

7. A lathe toolbit with a rake angle of 20° is cutting a section of pipe with an inner diameter of 6” and an outer diameter of 6.25”. The cut has a depth of 0.010” and the chip has a thickness of 0.020”. If the lathe is turning at 200 rpm, and the measured cutting forces are F_c = 300 lb, and

F_t = 125lb,

a) what assumption must you make.
b) find the following values using a graphical or numerical solution: (Marks are only awarded for correct answers) F_s, F_N, F, N, τ, ϕ, μ, V_c, V_f, V_s.
c) what is the minimum horsepower required for the machine?
d) given that the tube is aluminum, use another method to find the required horsepower.

ans.

$$\alpha = 20\text{deg} \qquad F_c = 300\text{lbs} \qquad F_t = 125\text{lbs} \qquad t_1 = d = 0.010\text{in}$$

$$RPM = 200 \qquad t_2 = 0.020\text{in} \qquad D = \left(\frac{6 + 6.25}{2}\right) = 6.125\text{in}$$

a) reasonable assumptions are that we are performing orthogonal cutting. This means that we are cutting fully through the wall of the tube. We also want to assume that the effects of the different cutting speeds from the inside to the outside of the tube are negligible.

b)
$$r_c = \frac{t_1}{t_2} = 0.5 \qquad \phi = \operatorname{atan}\left(\frac{r_c \cos\alpha}{1 - r_c \sin\alpha}\right) = \operatorname{atan}(0.56676719) = 29.5\text{deg}$$

$$F = F_t\cos\alpha + F_c\sin\alpha = 220\text{lbs} \qquad N = F_c\cos\alpha - F_t\sin\alpha = 239\text{lbs}$$

$$F_s = F_c\cos\phi - F_t\sin\phi = 200\text{lbs} \qquad F_n = F_t\cos\phi + F_c\sin\phi = 257\text{lbs}$$

$$\mu = \frac{F}{N} = 0.92 \qquad \tau = \operatorname{atan}(0.92) = 42.6\text{deg}$$

$$V_c = \frac{RPM\pi D}{12} = \frac{200\pi(6.125)}{12} = 321fpm$$

$$V_s = \frac{321\cos 20}{\cos(29.5 - 20)} = 306fpm \qquad V_f = \frac{321\sin 29.5}{\cos(29.5 - 20)} = 160fpm$$

c)
$$HP_c = \frac{F_c V_c}{33000} = \frac{300(321)}{33000} = 2.9\text{HP}$$

For an efficient machine with no idle horsepower.

d)
$$Q = d(6.25 - 6)V_c 12 = 0.010(0.25)321(12) = 9.63\frac{\text{in}^3}{min}$$

$$HP_c = HP_u Q = 0.3(9.63) = 2.9\text{HP}$$

8. Calculate the machine tool spindle speeds for the following:
   a) Milling with a tungsten carbide tipped face cutter on a stainless steel work piece. C.S. = 65 m/min., cutter dia. = 150mm.
   b) Drilling with a High Speed Steel drill in Machine Steel work, with C.S. = 70 ft./min.,

and a drill diameter of 19/32”

c) Turning on a lathe with a High Speed Steel tool in a mild steel work piece. Surface cutting speed = 100 ft./min., and a workpiece diameter of 2.75”

d) Milling with a High Speed Steel cutter in tool steel work with a cutter speed of 60 ft./min., and a cutter diameter of 3/4”.

9. Short answer,
a) Why are ceramics normally provided as inserts for tools, and not as entire tools?
b) List the important properties of cutting tool materials and explain why each is important.

ans.

a) Ceramics are brittle materials and cannot provide the structural strength required for a tool.

b) hardness at high temperatures - this provides longer life of the cutting tool and allows higher cutting speeds.
toughness - to provide the structural strength needed to resist impacts and cutting forces
wear resistance - to prolong usage before replacement
doesn’t chemically react - another wear factor
formable/manufacturable - can be manufactured in a useful geometry

10. A turning cut was made in a magnesium workpiece with a feed of 0.050ipr. The cutting speed was 300 fpm, and the cutting force was measured as 200lbs. The lathe is 95% efficient and has an idle horsepower of 0.1HP. Using all of the provided information estimate the horsepower required for the cut.

ans.

$$HP_c = \frac{V_c F_c}{33000} = \frac{300\frac{ft}{min}(200lbs)}{33000\frac{ftlbs}{minHP}} = 1.82HP$$

$$HP_M = HP_I + \frac{HP_c c}{e} = 0.1HP + \frac{(1.82HP)(0.75)}{0.95} = 1.54HP$$

11. Develop an expression that is the ratio friction power over cutting power using the equations for orthogonal cutting power. Simplify the expression to be in terms of measured values (rake angle, Fc, Ft, and chip thicknesses).

ans.
$$R = \frac{W_f}{W_c} = \frac{\left(\frac{FV_f}{33000}\right)}{\left(\frac{F_c V_c}{33000}\right)} = \frac{FV_f}{F_c V_c} = \frac{(F_t \cos\alpha + F_c \sin\alpha)\left(\frac{V_c \sin\phi}{\cos(\phi - \alpha)}\right)}{F_c V_c}$$

$$R = \frac{(F_t \cos\alpha + F_c \sin\alpha)(\sin\phi)}{F_c \cos(\phi - \alpha)} = \frac{(F_t \cos\alpha + F_c \sin\alpha)}{F_c}\left(\frac{\sin\phi}{\cos(\phi - \alpha)}\right)$$

$$R = \frac{(F_t \cos\alpha + F_c \sin\alpha)}{F_c}\left(\frac{t_1}{t_2}\right)$$

12. A new lathe tool is to be used on cast iron work with a 6” diameter to make a 5” long rough cut in 3 passes. The operation conditions listed below were provided by the supplier or assumed. Calculate the parameters a) to e) as requested.

Cutting Speed = 300 fpm
Feed Rate = 0.008 ipr
Depth of Cut = 0.125”
Idle Horse Power = 0.25
Machine Efficiency = 0.90

a) Spindle RPM
b) Time to make the cut (min.)
c) Metal Removal Rate Q (in.^{3}/min.)
d) Cutting Horse Power (HP_c)
e) Minimum Machine Tool Motor HP.

13. Which of these statement is most correct?
a) a continuous chip with built up edge may result when we try to cut brittle metals.
b) a continuous chip will result when cutting very strong work materials.
c) a discontinuous chip will result when we use heavy feeds and speeds.
d) all of the above.

ans. C

14. One of the assumptions behind calculating orthogonal cutting forces is,
a) that the rake angle is positive.
b) that the tool is only cutting with one edge and one point.
c) the shear plane is a function of before and after chip thicknesses.
d) none of the above.

ans. C

15. Which of these statements is most correct?
a) the cutting pressure drops as cutting velocity decreases.

b) power required to cut each cubic inch drops as cutting velocity increases.
c) we can use the quantity of metal removed by itself to estimate the required horsepower of a machine tool.
d) all of the above.

ans. B

16. A new lathe tool is to be used on cast iron work with a 6” diameter to make a 36” long rough cut in 4 passes. The operation conditions listed below were provided by the supplier or assumed. Calculate the parameters a) to e) as requested.

Cutting Speed = 200 fpm
Feed Rate = 0.010 ipr
Depth of Cut = 0.100”
Idle Horse Power = 0.25
Machine Efficiency = 0.90

a) Spindle RPM
b) Time to make the cut (min.)
c) Metal Removal Rate Q (in.^{3}/min.)
d) Cutting Horse Power (HP_c)
e) Minimum Machine Tool Motor Horse Power.

ans. a) 127rpm, b) 113min., c) 2.4 ipm, d) 1.23 or 3.94HP, e) 1.62 or 4.63HP

$$D = 6\text{in} \quad CS = 200\frac{ft}{min} \quad f = 0.01ipr \quad d = 0.1\text{in} \quad HP_I = 0.25 \quad e = 0.9$$

a) $$rpm = \frac{CS}{\pi d} = \frac{200\frac{ft}{min}}{\pi(6\text{in})} = \frac{200(12)in}{\pi(6)\text{in min}} = 127rpm$$

b) $$T = \frac{L}{f(rpm)} = \frac{36\text{in}}{0.01ipr(127rpm)} = 28.35\text{min}$$ (for one pass)

c) $$Q = 12fdCS = 12(0.01)(0.1)(200) = 2.4\frac{\text{in}^3}{min}$$

d) $$HP_c = HP_uQ = \left(\frac{0.5 + 1.6}{2}\right)2.4 = 2.5\text{HP}$$

e) $$HP_M = HP_I + \frac{HP_C}{e} = 0.25 + \frac{2.5}{0.9} = 3.0\text{HP}$$

17. a) Define machinability. b) What determines the machinability of a metal?

20. What factors will affect surface finish?

21. Sketch a single edge cutting tool and label the a) face, b) flank, c) nose, d) cutting edge, e) relief, f) shank.

22. Why is the cutting speed important? What will happen at different cutting speeds, from very slow to very fast?

23. We have set up a lathe and are doing an orthogonal cut. The feed rate of the lathe is 0.1mm, and the chip thickness after the cut is 0.2mm. The depth of the chip being cut is 5mm. The surface cutting speed of the tool is 2m/s. The tool has a rake angle of 10deg. The tangential force is measured as 200N, and the cutting force is 500N. a) Calculate the shear force and velocity. b) Calculate the total energy produced in the cut, c) Calculate the energy used to shear d) Explain the difference between the total and the shear energy. [based on Kalpakjian]

ans.

Given,

$$t_1 = 0.1mm \qquad \alpha = 10° \qquad V_c = 2\frac{m}{s} \qquad F_c = 500N$$

$$t_2 = 0.2mm \qquad depth = 5mm \qquad F_t = 200N$$

Find the total power and shear power.

$$W_c = F_c V_c = (500N)\left(2\frac{m}{s}\right) = 1000W\left(\frac{1HP}{746W}\right) = 1.34HP$$

$$r_c = \frac{t_1}{t_2} = \frac{0.1}{0.2} = 0.5$$

$$\phi = \operatorname{atan}\left(\frac{r_c\cos\alpha}{1 - r_c\sin\alpha}\right) = 28.3°$$

$$F_S = F_c\cos\phi - F_t\sin\phi = 345N$$

$$V_S = \frac{V_c\cos\alpha}{\cos(\phi - \alpha)} = 2.07\frac{m}{s}$$

$$W_S = F_S V_S = 714W\left(\frac{1HP}{746W}\right) = 0.96HP$$

Finally the ratio between the cutting power and the shear power

$$\frac{W_S}{W_c} = \frac{0.96}{1.34} = 0.71$$

24. How is machining different than other processes?

25. What is the difference between a roughing and finishing operation? How does this affect the workpiece and the power consumed?

26. What type of chip is expected at higher cutting speeds?

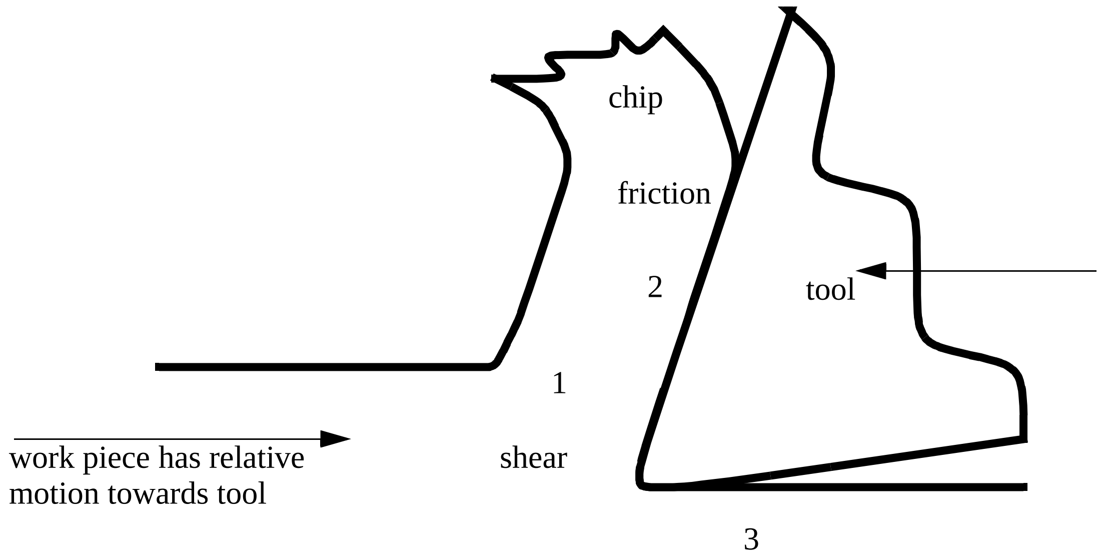
27. Does the friction power in cutting increase more with a feed or speed increase?

28. Why does cost typically increase for finishing operations.

29. Explain the correction factor ‘c’ used with the HPu values.
(ans. the HPu values are not linear, and ‘c’ corrects for these non-linear values)

5.5 TEMPERATURES IN CUTTING

• There are three main sources of heat when cutting,
  1. Heat is produced as the tool deforms (works) the metal
  2. Friction on the cutting face
  3. Friction on the tool flank



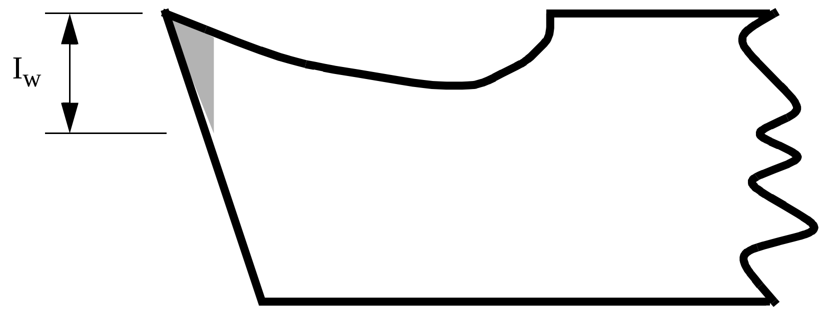
• Heat is mostly dissipated by,
  1. The discarded chip carries away heat
  2. Coolant will help draw away heat
  3. The workpiece acts as a heat sink
  4. The cutting tool will also draw away heat.
  ** factors 1 & 2 dissipate 75 to 80%, factors 3 and 4 dissipate 10% each [Krar,]

5.6 TOOL WEAR

• Tool wear is still a significant problem in cutting.

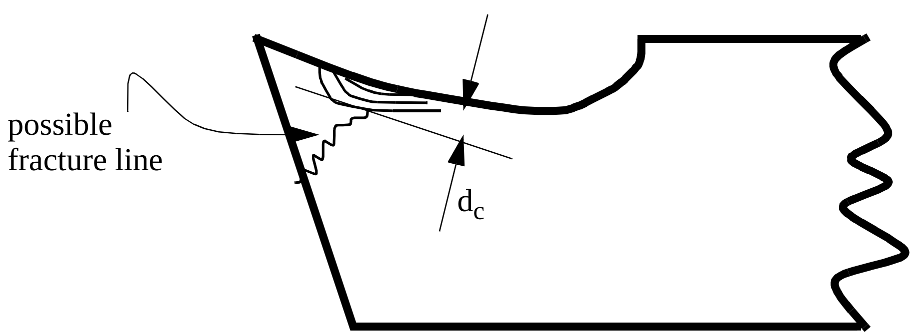
• Typical types of tool wear include,
  - Flank wear
  - Crater wear

• Flank wear - the point of the tool degrades



This wear controls tool life, and will change work dimensions

• Crater wear also decreases tool life

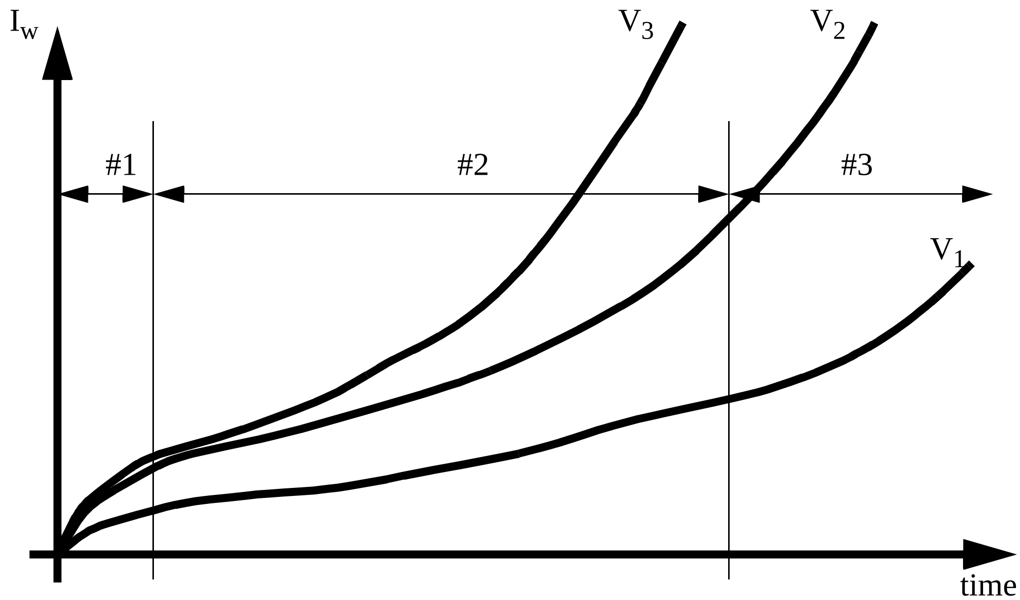


where,

d_c = crater depth

• Tool failure can typically grouped under one of the following categories,
  - Complete Failure - the tool is unusable
  - Flank Failure - this can be estimated with maximum l_w values,
    • Roughing Cuts
      0.03” for carbide tools
      0.06” for high speed steel
    • Finishing Cuts
      0.010” for carbides
      0.015” for high speed steel
  - Work surface finish is inadequate
  - Work dimension outside tolerance

• Flank wear can be discussed as a function of time,



where,

V_1, V_2, V_3 = cutting velocities where $V_3 > V_2 > V_1$
#1 - In this region the tool point is starting to dull
#2 - A typical tool wear region
#3 - This zone is temperature sensitive

• General notes of concern are,
- The main factor in tool wear is temperature
- The main factor in tool life is cutting speed
- Critical temperatures for High Speed Steels are 1150°F and for carbides it is 1600°F
- A higher velocity will increase temperature more than an increase in feed for the same mrr
- A higher feed will increase the tool forces

5.7 CUTTING TOOL MATERIALS

• These materials generally need to withstand high temperatures, high forces, resist corrosion, etc.

• The names used for certain materials will be brand names, and so various manufacturers may be calling the same material, different names.

• The List below shows some commercial tool materials

CBN - Cubic Boron Nitride
ceramic -

HSS - High Speed Steel
PCD - PolyCrystalline Diamond
sialon -
WC - Tungsten Carbide
coated WC - Tools coated with Tungsten Carbide

5.7.1 A Short List of Tool Materials

• Carbon Steels
- Limited tool life. Therefore, not suited to mass production
- Can be formed into complex shapes for small production runs
- low cost
- suited to hand tools, and wood working
- Carbon content about 0.9 to 1.35% with a hardness ABOUT 62°C Rockwell
- Maximum cutting speeds about 26 ft/min. dry
- The hot hardness value is low. This is the major factor in tool life.

• High Speed Steel
- an alloyed steel with 14-22% tungsten, as well as cobalt, molybdenum and chromium, vanadium.
- Appropriate heat treating will improve the tool properties significantly (makers of these steels often provide instructions)
- can cut materials with tensile strengths up to 75 tons/sq.in. at speeds of 50-60 fpm
- Hardness is in the range of 63-65°C Rockwell
- The cobalt component give the material a hot hardness value much greater than Carbon Steels
- Used in all type of cutters, single/multiple point tools, and rotary tools

• Stellite
- a family of alloys made of cobalt, chromium, tungsten and carbon
- The material is formed using electric furnaces, and casting technique, and it cannot be rolled, or worked.
- The material has a hardness of 60-62°C Rockwell without heat treating, and the material has good hot hardness properties
- Cutting speed of up to 80-100 fpm can be used on mild steels
- The tools that use this method either use inserts in special holders, or tips brazed to carbon steel shanks

• Tungsten Carbide
- Produced by sintering grains of tungsten carbide in a cobalt matrix (it provides toughness).
- Other materials are often included to increase hardness, such as titanium, chrome, molybdenum, etc.

- Compressive strength is high compared to tensile strength, therefore the bits are often brazed to steel shanks, or used as inserts in holders
- These inserts may often have negative rake angles
- Speeds up to 300 fpm are common on mild steels
- Hot hardness properties are very good
- coolants and lubricants can be used to increase tool life, but are not required.
- special alloys are needed to cut steel

• Ceramics
  - sintered or cemented ceramic oxides, such as aluminum oxides sintered at 1800°F
  - Can be used for turning and facing most metals, except for nimonic alloys and titanium. Mild steels can be cut at speeds up to 1500 fpm.
  - These tools are best used in continuous cutting operations
  - There is no occurrence of welding, or built up edges
  - coolants are not needed to cool the workpiece
  - Very high hot hardness properties
  - often used as inserts in special holders

• Diamonds
  - a very hard material with high resistance to abrasion
  - very good for turing and boring, producing very good surface finish
  - operations must minimize vibration to prolong diamond life
  - also used as diamond dust in a metal matrix for grinding and lapping. For example, this is used to finish tungsten carbide tools

• Cemented Oxides
  - produced using powder metallurgy techniques
  - suited to high speed finishing
  - cutting speeds from 300 to 7500 fpm
  - coolants are not required
  - high resistance to abrasive wear and cratering

5.8 TOOL LIFE

• Tool life is the time a tool can be reliably be used for cutting before it must be discarded/ repaired.

• Some tools, such as lathe bits are regularly reground after use.

• A tool life equation was developed by Taylor, and is outlined below,

$$V \times T^{n} = C$$

where,

V = cutting velocity in ft./min.
T = tool life in minutes
n = a constant based on the tool material
C = a constant based on the tool and work

For example, if we are turning a 1” diameter bar, and we have a carbide tool, we want to have the tool last for 1 shift (8 hours) before a change is required. We know that for carbide tools n=0.2, and when the bar was cut with a velocity of 400 ft./min. the tool lasted for 2 hours. What RPM should the lathe be set at?

First find the C value for the equation,

$$400 \times (2 \times 60)^{0.2} = C =$$

Next, find the new cutting speed required,

$$V \times (8 \times 60)^{0.2} =$$

Finally, convert cutting velocity to RPM,

$$RPM = \frac{12 \times V}{\pi D} =$$

- An important relationship to be considered is the relationship between cutting speed and tool life,

$$V \times T^n = C$$

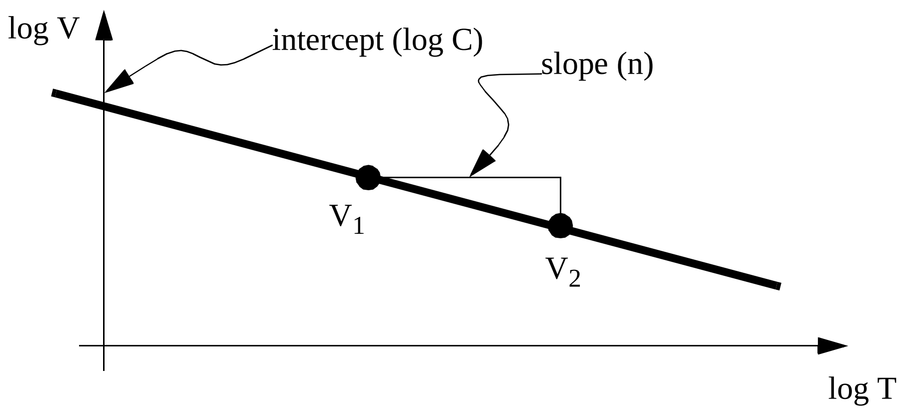
$$\therefore \log(V \times T^n) = \log C$$

$$\therefore \log V + \log T^n = \log C$$

$$\therefore \log V + n \log T = \log C$$

$$\therefore \log V = -n \log T + \log C$$

This function can be plotted on log scales as a linear function,



We can find the slope of the line with a two point interpolation,

$$n = \frac{\log V_1 - \log V_2}{\log T_2 - \log T_1}$$

Some examples of values are, (note that this is related to ‘n’)

High Speed Steel Tool	n = 0.10 to 0.125
Carbide Tool	n = 0.125 to 0.25
Ceramic Tool	n > 0.25

• Although the previous equation is fairly accurate, we can use a more complete form of Taylor’s tool life equation to include a wider range of cuts.

$$VT^n d^x f^y = C$$

where,
d = depth of cut
f = feed rate
x, y = calculated constants

5.8.1 The Economics of Metal Cutting

• As with most engineering problems we want to get the highest return, with the minimum investment. In this case we want to minimize costs, while increasing cutting speeds.

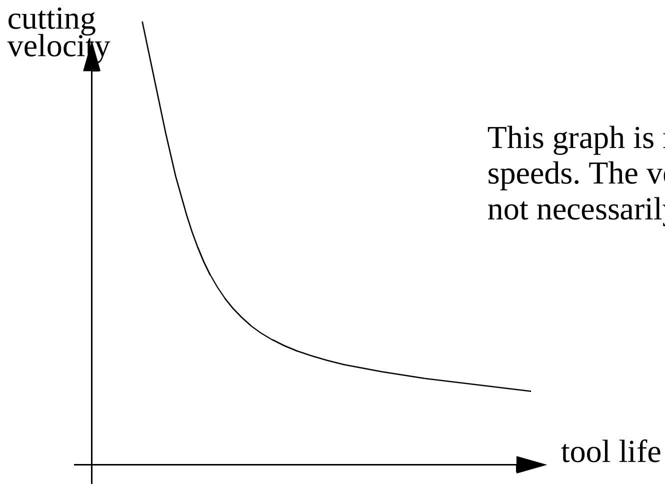
• EFFICIENCY will be the key term - it suggests that good quality parts are produced at reasonable cost.

• Cost is a primarily affected by,
  - tool life
  - power consumed

• The production throughput is primarily affected by,
  - accuracy including dimensions and surface finish
  - mrr (metal removal rate)

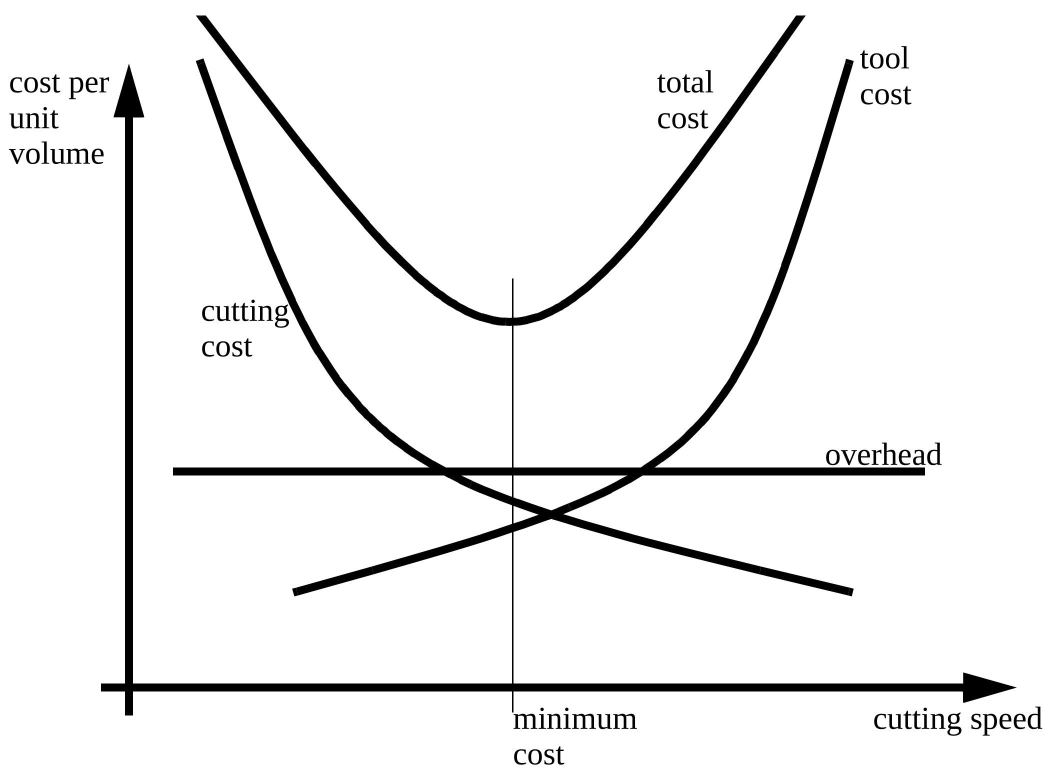
• The factors that can be modified to optimize the process are,
  - cutting velocity (biggest effect)
  - feed and depth
  - work material
  - tool material
  - tool shape
  - cutting fluid

• We previously considered the log-log scale graph of Taylor's tool life equation, but we may also graph it normally to emphasize the effects.



This graph is representative for most reasonable cutting speeds. The velocities at the high and low ranges do not necessarily exhibit the same relationship.

• There are two basic conditions to trade off,
  - Low cost - exemplified by low speeds, low mrr, longer tool life
  - High production rates - exemplified by high speeds, short tool life, high mrr
  *** There are many factors in addition to these, but these are the most commonly considered



• A simplified treatment of the problem is given below for optimizing cost, First lets look at costs for a cutting tool over the life of a tool,

$$C_t = c_1 + c_2 + c_3$$

where,

C_t = cost per cutting edge
c_1 = the cost to change a tool
c_2 = the cost to grind a tool per edge
c_3 = the cost of the tool per edge

and,

$$c_1 = t_1 \times R_c$$

$$c_2 = t_2 \times \frac{R_s}{N_1}$$

$$c_3 = \frac{C_T}{N_1 \times (N_2 + 1)}$$

where,

t_1 = tool change time
t_2 = tool grind time in minutes
R_c = cutting labour + overhead cost
R_s = grinding labor + overhead cost
C_T = cost of the original tool
N_1 = the number of cutting edges to grind
N_2 = the maximum number of regrinds

and,

$$C_c = R_c \times T$$

where,

C_c = cutting operation cost over life of tool, per edge
T = tool life

Next, lets consider the effects of metal removal rate,

$$Q_T = V \times T \times f \times c \tag{1}$$

where,

Q_T = metal removal rate per edge
V = cutting velocity
f = tool feed rate
c = depth of width of the cut

consider the life of the tool,

$$V \times T^n = C \text{ (Taylors tool life equation)}$$

$$\therefore V = \frac{C}{T^n} \tag{2}$$

Now combine tool life (2) with the mrr (1),

$$Q_T = V \times T \times f \times c = \frac{C}{T^n} \times T \times f \times c = \frac{C \times f \times c}{T^{n-1}}$$

At this point we have determined functions for cost as a function of tool life, as well as the metal removal rates. We can now proceed to find cost per unit of material removed.

$$C_u = \frac{C_c + C_t}{Q_T} = \frac{T^{n-1}}{C \times f \times c}(R_c \times T + C_t)$$

Using some basic calculus, we can find the minimum cost with respect to tool life.

$$\frac{dC_u}{dT} = \left(\frac{1}{C \times f \times c}\right)(R_c \times n \times T^{n-1} + C_t \times (n-1) \times T^{n-2}) = 0$$

$$\therefore R_c \times n \times T = -C_t \times (n-1)$$

$$\boxed{\therefore T = \frac{-C_t \times (n-1)}{R_c \times n} = \frac{C_t}{R_c}\left(\frac{1-n}{n}\right)}$$

• We can also look at optimizing production rates, There are two major factors here when trying to increase the mrr. We can have a supply of tools by the machine, and as the tools require replacement, the only down-time involved is the replacement of the tool.

This gives us an average rate of production,

$$R_p = \frac{Q_T}{T + t_1}$$

where,

R_p = average rate of production

recall from before that,

$$Q_T = \frac{Cfc}{T^{n-1}}$$

now substituting in gives,

$$R_p = \frac{\left(\frac{Cfc}{T^{n-1}}\right)}{T + t_1} = Cfc(T^n + t_1)^{-1}$$

We can now optimize the production rate,

$$\frac{dR_p}{dT} = Cfc[-(T^n + t_1)^{-2} + (nT^{n-1} + t_1)(T^n + t_1)^{-1}] = 0$$

$$\therefore (T^n + t_1)^{-2} = (nT^{n-1} + t_1)(T^n + t_1)^{-1}$$

$$\therefore 1 = (nT^{n-1} + t_1)(T^n + t_1)$$

$$\therefore 1 = nT^{2n-1} + nt_1T^{n-1} + t_1T^n + t_1^2$$

$$\therefore \log(1) = \log(nT^{2n-1}) + \log(nt_1T^{n-1}) + \log(t_1T^n) + \log(t_1^2)$$

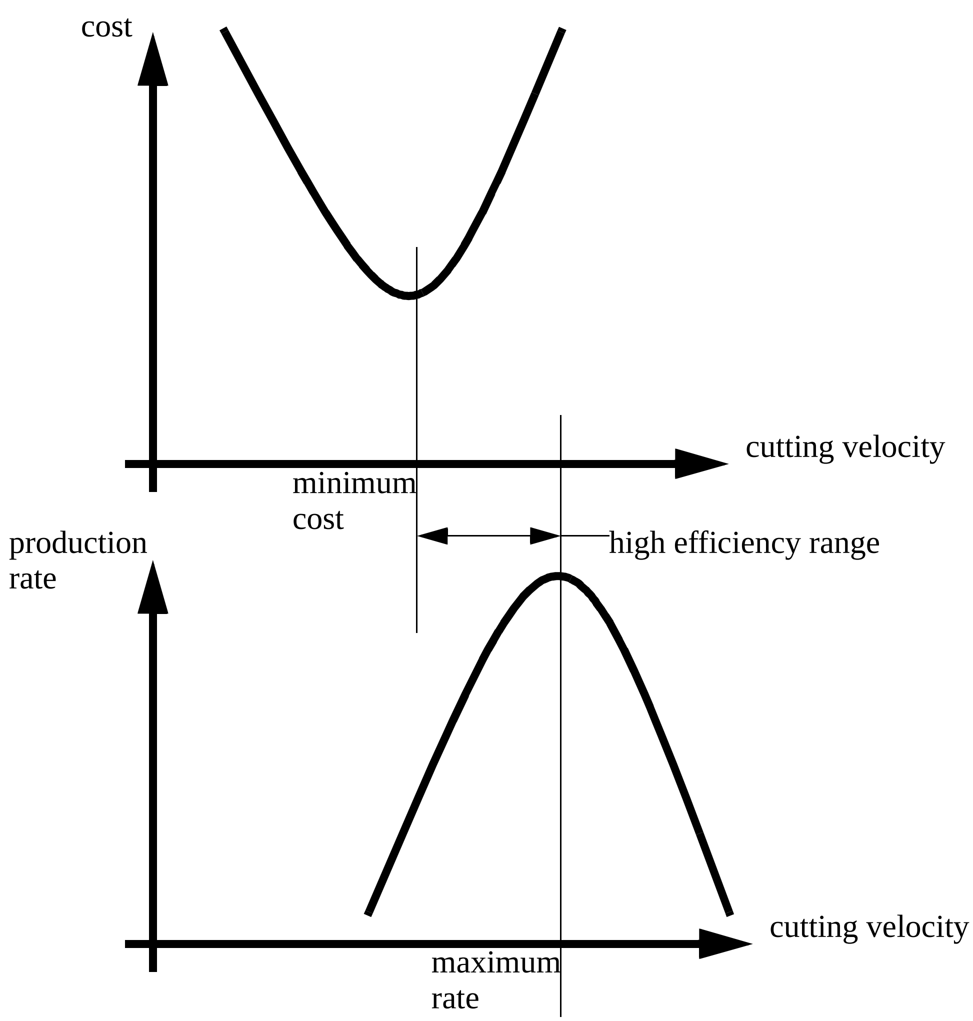
$$\therefore 0 = \log(n) + (2n-1)\log(T) + \log(nt_1) + (n-1)\log(T) + \log(t_1) + n\log(T) + \log(t_1^2)$$

$$\therefore 0 = 2\log(n) + (4n-2)\log(T) + 4\log(t_1)$$

$$\boxed{\therefore \log(T) = \frac{\log(n) + 2\log(t_1)}{1 - 2n}}$$

• We can now put the two optimums in perspective,

Since, $t_1 < C_t/R_c$ then tool life for maximum production is less than economical tool life and as a result, cutting velocity for maximum production is > velocity for lowest cost



5.9 REFERENCES

Ullman, D.G., The Mechanical Design Process, McGraw-Hill, 1997.

5.10 PRACTICE PROBLEMS

1. If a bar of SAE 1040 is to be turned with a high speed steel tool with a feed of 0.015” per revolution, and a depth of 0.050”. Previous experiments have revealed that the following cutting velocities yielded the following tool lives,

   90 fpm for 30 min.
   80 fpm for 90 min.
   75 fpm for 150 min.

   a) estimate the cutting speeds to get tool lives of 60 and 120 minutes.
   b) calculate the mrr at the two speeds found in part a).

2. Two tools are being compared for their costs. The table below summarizes the details of each tool. Find the economic tool life and cutting speed for each tool, and determine the least expensive tool.

Category	Tool A	Tool B
material	tungsten carbide	tungsten carbide
description	uses a brazed insert	uses a replaceable clamped insert
purchase price ($)	5.30	6.53
maximum # regrinds	6	8
# of cutting edges	1	# of cutting edges
regrind time (min.)	5.5 min/edge.	8 edges in 15 min.
regrind rate ($/hr)	16.20	regrind rate ($/hr)
tool change rate($/hr)	15.00	15.00
Taylor eqn. ‘n’	0.2	0.2
Taylor eqn ‘C’	500	500
tool change time (min.)	2	0.5

(ans. tool A T = 45.9 min., V = 232.6 fpm, tool B T = 11.73 min., V = 305.6 fpm, both A and B cost $0.062/min.)

3. What happens to the cutting process as the temperature rises?

ans. As temperatures rise both the tool and work change. Heat causes expansion, therefore the dimensions change, and accuracy decreases. Heat also causes decreased strength of the material. This causes faster wear in the tool, but also makes the work easier to cut.

4. We are going to estimate the effects of feedrate on tool life. Some simple calculations yield the Taylor tool life coefficients of n = 0.4 and a C = 400. Find the change in tool life (in %) when velocity drops by a) 20% and b) 40%. [based on Kalpakijian]

ans.

Given, $n = 0.4$ $c = 400$ for Taylor’s equation

for a) $f_v = 0.8$ b) $f_v = 0.6$ what is ft?

$$VT^n = C \quad \text{therefore} \quad (f_v V)(f_t T)^n = C$$

$$C = VT^n = (f_v V)(f_t T)^n$$

$$1 = f_v f_t^n$$

a) $f_v = 0.8$ $f_t = 1.75$ T is 75% higher

b) $f_v = 0.6$ $f_t = 2.59$ T is 259% higher

5. Some tools use coatings that reduce the coefficient of friction. How does this affect the cutting process?

ans. Reduced friction in cutting reduces heat in the chip and tool, and this will prolong tool life. The reduced friction also decreases the wear rate and prolongs tool life.

6. Describe the factors that are used to decide when a tool should be reconditioned, recycled or discarded.

ans. Two failures typically occur; wear and fracture. If a tool is worn, and the material and geometry permit, we can recondition a tool - grinding is common. If a tool is fractured or can’t be reconditioned, it can be discarded. In some cases tools contain parts that can be reclaimed, or materials that can be recycled.

7. As cutting temperatures rise materials expand. How does this affect the cutting process?

8. Consider that at a certain velocity we will get the lowest cost per piece. As the cutting velocity rises the cost per piece rises (but we will improve the production rate) what cost components rise or drop?

9. Describe at least two methods that generate heat during machining.

10. How does the heat generated during cutting affect the operation?

11. What are the main failure types found in tools? Where do these typically occur on the tool?

12. What does the parameter ‘n’ mean in Taylor’s tool life equation? How is ‘C’ different?

13. What properties are desired in a material for a cutting tool?

14. What are the main functions of cutting fluids?

15. We have been asked to calculate the cutting speeds that gives the maximum possible production rate and lowest cost for an existing job. The current tool will last for 4 hours if we cut at 300 fpm and 2 hours at 345 fpm. The following things are known about the job.

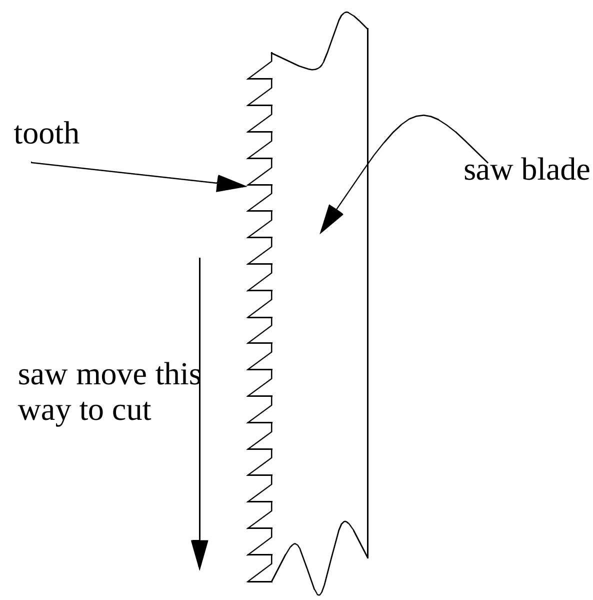
- the tool costs $6.50 and has 2 edges that can be reground 5 times before discarding.
- it takes 5 minutes to change the tool, and 10 minutes to regrind it.
- the labor rates for the operators is $25.00/hr.
- the tool room labor rate is $35.00/hr for regrinding tools.

(ans. Vecon = 525fpm, Vcost = 404)

6. SAWS

• Basically a saw drags a number of cutting teeth through work to cut a thin slot. When done, two major piece can be separated.

• The basic saw blade look like,



• Saw types,

Circular saws - use round blades rotated at high speeds.

Band saw - a band is in one continuous loop-, like a ribbon.

Hack saw - a small blade much like a steel ruler. This is moved back and forth (it reciprocates) to provide the cutting action.

• Saw operations include,

Cutoff - one smaller piece of stock is cut from a larger one.

Contouring - a bandsaw is used to cut a non-straight path in an object, often this step precedes other machining operations, such as drilling.

Stack Cutting - multiple pieces are cut at the same time.

Shaping - Chunks are cut out of a larger piece.

Angular Cuts - such as cutting a side hole in a pipe.

Internal Cuts - the entire hole is enclosed in the material.

Ripping - Long cuts to separate parts into halves.

6.1 SPEEDS AND FEEDS

6.2 PRACTICE PROBLEMS

1. A 1/2” thick steel plate is being cut on a band saw. The saw blade has 10 teeth/in. and with a feed rate of 0.002”/tooth and is traveling at 200 fpm. How many inches per minute may be cut?

2. When sawing, how many teeth of the blade are cutting at any time?

7. DRILLING

• A very common operation that cuts cylindrical holes.

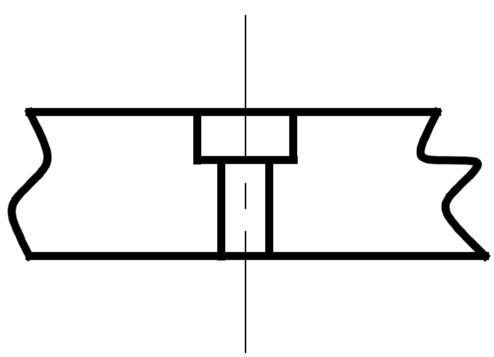
7.1 TYPES OF DRILL PRESSES

• General type of drill presses in use are,
  • Sensitive - typically belt driven, and the bit is fed by hand. There are a limited choice of speeds. A bench top machine
  • Vertical or Pillar - has a heavy frame to support a wider range of work. The table height is adjustable, and power speeds and feeds are available.
  • Radial Arm - For very large and heavy work. The arm is power driven for the height location. The drilling head traverses the swinging arm. The workpiece remains stationary on the machine base, or work table. The machine spindle is moved to the location required.

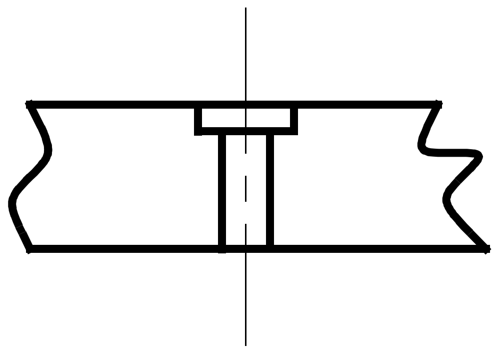
• More specialized drill presses are,
  • Gang Type - several spindles/or stations are mounted on one long table
  • Multi Spindle - There are many spindles mounted on one head to allow many holes to be drilled simultaneously (e.g., up to 24)
  • Numerical Control Type - The machine can automatically change tooling with a turret or automatic tool changer. Speeds, feeds and table position are controlled using a computer program.

7.2 TYPICAL DRILL PRESS OPERATIONS

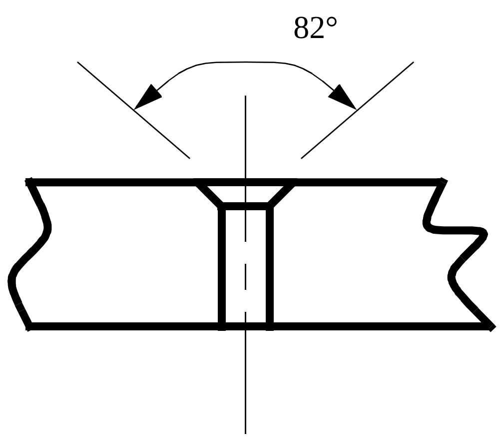
• Counter Bores - Allows the head of cap screws to be sunk beneath a surface



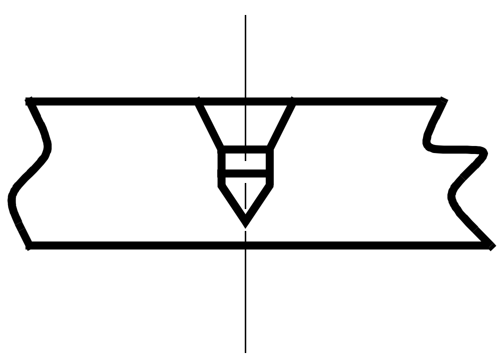
• Spot Face - Allows the head of a bolt to be sunk beneath the surface. This is basically a shallow counter bore.



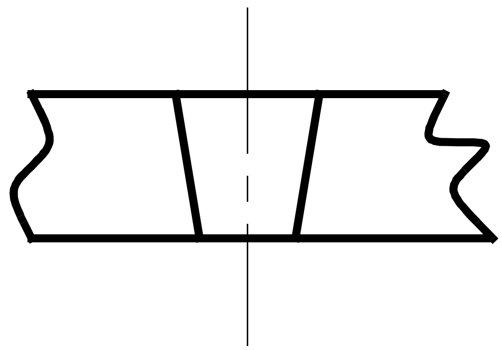
• Counter Sink - Allows counter sunk head screws to be sunk beneath a surface.



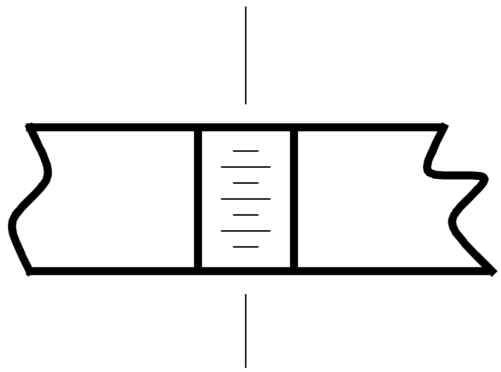
• Center Drilling - Allows parts to be mounted between centers, on lathes typically.



• Tapers Holes - these holes can be cut using reamers.



• Threaded Holes - Taps can be used to add threads to holes



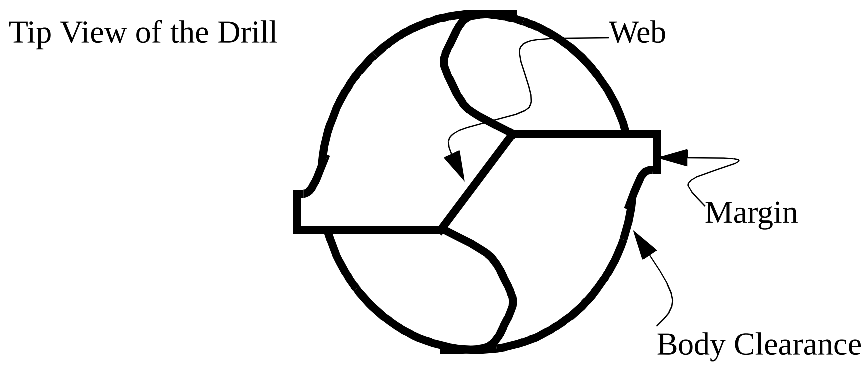
• High tolerance finishes for holes can be made with boring or reaming.

7.3 TYPICAL DRILL BITS

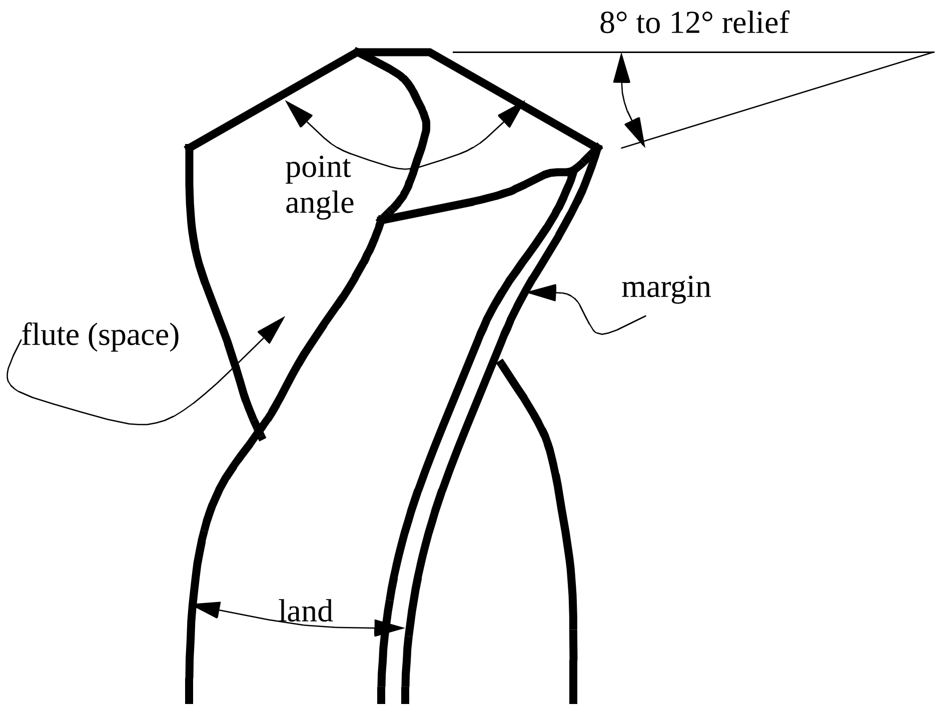
• The twist drill does most of the cutting with the tip of the bit.

• There are flutes to carry the chips up from the cutting edges to the top of the hole where they are cast off.

• Some of the parts of a drill bit are diagramed below as viewed from the cutting tip of the drill,



• Some other features of the drill bit are shown below for a side view of the drill bit,



• Typical parameters for drill bits are,
 - Material is High Speed Steel
 - Standard Point Angle is 118°

• Harder materials have higher point angles, soft materials have lower point angles.

• The helix results in a positive cutting rake.

• Drill bits are typically ground (by hand) until they are the desired shape. When done grinding, the lips should be the same length and at the same angle, otherwise and oversized hole may be produced.

• Drill sizes are typically measured across the drill points with a micrometer

• Typical drill sizes are,
  - FRACTIONAL - 1/64” to 3 1/4” dia. in 1/64” steps
  - NUMBER - #1 = 0.228” dia. to #80 = 0.0135” dia.
  - LETTER - A = 0.234” dia. to Z = 0.413” dia.
  - METRIC - 0.4mm dia. to 50mm dia.

DRILL #	dia. (in.)	DRILL #	dia. (in.)	DRILL #	dia. (in.)	DRILL #	dia. (in.)
1	0.2280	25	0.1495	49	0.0730	73	0.0240
2	0.2210	26	0.1470	50	0.0700	74	0.0225
3	0.2130	27	0.1440	51	0.0670	75	0.0210
4	0.2090	28	0.1405	52	0.0635	76	0.0200
5	0.2055	29	0.1360	53	0.0595	77	0.0180
6	0.2040	30	0.1285	54	0.0550	78	0.0160
7	0.2010	31	0.1200	55	0.0520	79	0.0145
8	0.1990	32	0.1160	56	0.0465	80	0.0135
9	0.1960	33	0.1130	57	0.0430	81	0.0130
10	0.1935	34	0.1110	58	0.0420	82	0.0125
11	0.1910	35	0.1100	59	0.0410	83	0.0120
12	0.1890	36	0.1065	60	0.0400	84	0.0115
13	0.1850	37	0.1040	61	0.0390	85	0.0110
14	0.1820	38	0.1015	62	0.0380	86	0.0105
15	0.1800	39	0.0995	63	0.0370	87	0.0100
16	0.1770	40	0.0980	64	0.0360	88	0.0095
17	0.1730	41	0.0960	65	0.0350	89	0.0091
18	0.1695	42	0.0935	66	0.0330	90	0.0087
19	0.1660	43	0.090	67	0.0320	91	0.0083
20	0.1610	44	0.0860	68	0.0310	92	0.0079
21	0.1590	45	0.0820	69	0.0292	93	0.0075
22	0.1570	46	0.0810	70	0.0280	94	0.0071
23	0.1540	47	0.0810	71	0.0260	95	0.0067
24	0.1520	48	0.0785	72	0.0250	96	0.0063
						97	0.0059

Letter size	dia. (in.)	Letter size	dia. (in.)
A	0.234	N	0.302
B	0.238	O	0.316
C	0.242	P	0.323
D	0.246	Q	0.332
E	0.250	R	0.339
F	0.257	S	0.348
G	0.261	T	0.358
H	0.266	U	0.368
I	0.272	V	0.377
J	0.277	W	0.386
K	0.281	X	0.397
L	0.290	Y	0.404
M	0.295	Z	0.413

• Some standard drill types are,
  - Straight Shank - this type is held in a chuck
  - Taper shank - this type is held in a sleeve, and a machine spindle. A drift may also be used.

• Some other types of drills used are,
  - Core drills - a drill with a small helix, and 3 or 4 flutes. This is used for light drilling, such as opening holes in castings.
  - High helix - When drilling a deep hole in a soft material these drills are used to help remove chips
  - Straight fluted - Used to drill soft metals and plastics. The straight flutes prevent the bit from digging in.
  - Centre drills - A drill with a small entry tip, and a widening profile. The result is a hole that has a conical shape on the outside, that may be used to mount the part between centres, or to act as a guide for a larger drill.

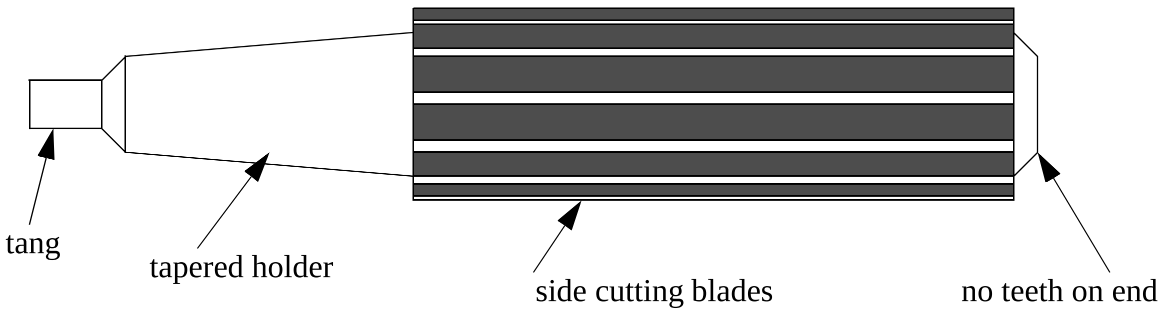
• Typically an allowance of a third of the drill bit diameter is given for the tip of the drill.

• Center Drill Sizes [Krar],

Regular Size	Work Dia. (in.)	Countersink dia. (in.)	Drill point dia. (in.)	Body Size (in.)
1	3/16-5/16	3/32	3/64	1/8
2	3/8-1/2	9/64	5/64	3/16
3	5/8-3/4	3/16	7/64	1/4
4	1-1.5	15/64	1/8	5/16
5	2-3	21/64	3/16	7/16
6	3-4	3/8	7/32	1/2
7	4-5	15/32	1/4	5/8
8	over 6	9/16	5/16	3/4

7.3.1 Reamers

• Reamers are a special class of drill. They are used after a hole has been drilled near to final size. The reamers is then used to remove a small quantity of material, and finish the hole with a good surface texture, roundness, and alignment.



• These are often used to provide holes for bearings, parallel and taper dowels, and various fits with a shaft.

• These are typically made of High Speed Steel, or with carbide tips.

• The main body contains many straight and helical flutes. The tip does not contain any cutting edges.

• Various types are,
  - Parallel Reamer - Straight fluted reamer held in a drill press spindle with a tapered shank.
  - Parallel Hand - Straight flutes, but held in a hand tap wrench.
  - Taper Reamers - has a taper from one end to the other. These can be used in a spindle (tapered shank), or by hand (for a taper wrench).
  - Adjustable Reamer - This uses inserted blades.

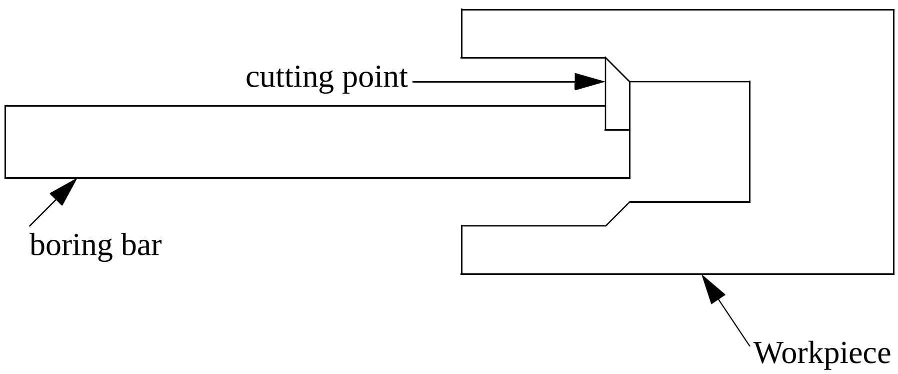
• Recommended allowances and speeds for reaming [Krar],

Hole Size (in.)	Allowance (in.)
1/4	0.010
1/2	0.015
3/4	0.018
1	0.020
1.25	0.022
1.5	0.025
2	0.030
3	0.045

Material	Speed (ft/min)
Aluminum	130-200
Brass	130-180
Bronze	50-100
Cast Iron	50-80
Machine Steel	50-70
Steel Alloys	30-40
Stainless Steel	40-50
Magnesium	170-270

7.3.2 Boring

• Boring is used for high quality finished.



• In boring the tool can be rotated, or the work can be rotated.

7.3.3 Taps

• Taps can use for both internal and external threads.

• A typical set of hand taps consists of
  - #1 Taper
  - #2 Plug
  - #3 Bottoming

• There are flutes in the taps to help remove chips, to provide cutting edges, and channels for lubrication.

• There are a number of sets of threads available,
  - UNC (Unified National Course)
  - UNF (Unified National Fine)
  - ACME
  - Metric

• To create one of these holes, we must first drill a hole that is slightly smaller. For example,

5/8 - 11 - UNC → outside diameter = 5/8 = 0.625”
11 threads per inch (T.P.I.)
Unified National Coarse is the tooth profile

The tap drill size is Outside Diameter - 1/T.P.I. for UNC, UNF, Metric threads.

Therefore, the Tap Drill Size (TDS) is,

T.D.S. = 0.625” - 1/11” = 17/32”

• Some setups associated with taps are,
  - alignment of the tap in a drill press
  - use of taping attachments

• NF/NC Thread Tap Drill Sizes [Krar],

National Coarse (NC)

Tap Size	TPI	Tap Drill Size
#5	40	#38
#6	32	#36
#8	32	#29
#10	24	#25
#12	24	#16
1/4	20	#7
5/16	18	F
3/8	16	5/16
7/16	14	U
1/2	13	27/64
9/16	12	31/64
5/8	11	17/32
3/4	10	21/32
7/8	9	49/64
1	8	7/8
1-1/8	7	63/64
1-1/4	7	1-7/64
1-3/8	6	1-7/32
1-1/2	6	1-11/32
1-3/4	5	1-9/16
2	4-1/2	1-25/32

National Fine (NF)

Tap Size	TPI	Tap Drill Size
#5	44	#37
#6	40	#33
#8	36	#29
#10	32	#21
#12	28	#14
1/4	28	#3
5/16	24	1
3/8	24	Q
7/16	20	25/64
1/2	20	29/64
9/16	18	33/64
5/8	18	37/64
3/4	16	11/16
7/8	14	13/16
1	14	15/16
1-1/8	12	1-3/64
1-1/4	12	1-11/64
1-3/8	12	1-19/64
1-1/2	12	1-27/64

7.4 DRILLING PROCESS PARAMETERS

• The parameters for drilling are found in almost the same way as for lathes,

$$CS = rpm \times C$$

$$C = \frac{\pi D}{12} = \frac{\pi D}{1000}$$

$$rpm = \frac{12 \times CS}{\pi \times D} = \frac{1000 \times CS}{\pi \times D}$$

imperial metric

where,

CS = cutting speed (fpm or m/s) - can be selected from tables
rpm = revolutions per minute of the machine spindle
C = circumference of the drill bit (ft. or m)
D = diameter of drill bit (in. or mm)

$$T = \frac{L}{F} = \frac{L}{rpm \times F}$$

$$C = T \times R$$

where,

L = length of cut (in. or mm)
F = feed rate (in./rev. or mm/rev.) - found in tables
R = Machine cost ($/min.)

• Typical high speed drill speeds are, [Krar]

Drill dia. (in.)	steel casting 40 fpm	tool steel 60 fpm	cast iron 80 fpm	machine steel 100 fpm	brass/aluminum 200 fpm
1/16	2445	3665	4890	6110	12225
1/	1220	1835	2445	3055	6110
3/16	815	1220	1630	2035	4075
1/4	610	915	1220	1530	3055
5/16	490	735	980	1220	2445
3/8	405	610	815	1020	2035
7/16	350	525	700	875	1745
1/2	305	460	610	765	1530
5/8	245	365	490	610	1220
3/4	205	305	405	510	1020
7/8	175	260	350	435	875
1	155	230	305	380	765

• Consider also the typical feeds for drilling, [Krar]

Drill dia. (in.)	Feed per Rev. (in.)
1/8 or less	0.001 to 0.002
1/8 to 1/4	0.002 to 0.004
1/4 to 1/3	0.004 to 0.007
1/2 to 1	0.007 to 0.015
1 to 1.5	0.015 to 0.025

7.4.1 The mrr For Drilling

• considering the parameters defined in the discussion of speeds and feeds, etc, the mrr is given below,

$$mrr = A \times F \times rpm = \frac{\pi D^2}{4} \times F \times rpm$$

where,

A = cutting area of the drill bit (a cross section)

7.5 PRACTICE PROBLEMS

1. What would happen if a drill without flutes was used?

2. If we want a hole with a 1/2-14-UNC thread, what size of tap drill should be used?

3. What type of drill press is suitable for drilling holes in car engine blocks? Justify your answer.

4. Which of these statements is not correct?
   a) work is not moved on a radial arm drill press.
   b) automatic feeds are available on sensitive drill presses.
   c) multispindle drill presses always drill multiple holes at once.
   d) all of the above.

5. Which of these statements is correct?
   a) a margin of a drill bit does most of the cutting.
   b) the relief angle on the tip of the drill bit makes it not a conical shape.
   c) a large drill bit point angle is useful for cutting soft materials.
   d) none of the above.

6. Which of the following statements is not correct?
   a) core drills have 3 or 4 flutes.
   b) high helix drills help in chip removal.
   c) straight fluted drills are used for sheet metal.
   d) centre drills are for long holes, such as gun barrels.

7. Which of the following is not a typical drill press operation?
   a) counter boring.
   b) spot facing.
   c) counter sinking.
   d) none of the above.

8. Which of the statements is most correct?
   a) reamers are used to finish holes with accuracies not possible when a normal drill is used.
   b) adjustable taps will cut a wide variety of threaded holes.
   c) taps and reamers can both be used without a machine tool.
   d) none of the above.

9. Given a hole that is to be drilled then reamed to 3.000”, develop a process plan including speeds and feeds.

10. We want to drill a hole that is 2.369” in diameter. If we know that the accuracy the shop can provide for drilling is +0.030” to -0.010”,
   a) what is an appropriate fractional drill size to use?
   b) what operation might follow?

11. Calculate the machine tool spindle speeds for the following,
    a) drilling with a 19/32” high speed steel bit in mild steel. The CS is 70 ft./min.

12. We are to drill 6 holes in a 2” thick mild steel plate. The plate is held in a jig. We are using a 63/64” high speed steel drill, and the suggested parameters are CS = 80 ft./min. with a feed of 0.004”/rev. After drilling each hole is to be finished with a 1.0” diameter reamer. If the suggested parameters for the reamer are CS = 80 ft./min. with a feed of 0.010”/rev.,
    a) calculate the time to do all of the operations (and make allowances for drill point travel)
    b) find the cost to produce 500 parts when each part needs 3 minutes for setup (no operation), labor rates are $25/hr., and overhead is $25/hr.

13. Which of these statements is not correct?
    a) work is not moved on a radial arm drill press.
    b) automatic feeds are available on sensitive drill presses.
    c) multispindle drill presses must always drill multiple holes at once.
    d) all of the above.

ans. B

14. Which of these statements is correct?
    a) a margin of a drill bit does most of the cutting.
    b) the relief angle on the tip of the drill bit makes it a conical shape.
    c) a large drill bit point angle is useful for cutting soft materials.
    d) none of the above.

ans. D

15. Which of the following statements is not correct?
    a) core drills have a hollow center to remove chips.
    b) high helix drills help in chip removal.
    c) straight fluted drills are used for sheet metal.
    d) centre drills are for long holes, such as gun barrels.

ans. A or D

16. Which of the following is not a typical drill press operation?
    a) counter boring.
    b) spot facing.
    c) counter sinking.
    d) none of the above.

ans. D

17. Which of the statements is most correct?
    a) reamers are used to finish holes with accuracies not possible when a normal drill is used.

b) adjustable taps will cut a wide variety of threaded holes.
c) taps and reamers can both be used without a machine tool.
d) none of the above.

ans. A

18. What are functions of the following parts of a drill bit. a) body, b) web, c) point, d) tang, e) margin, f) flutes, g) body clearance.

19. What are the purposes of the following drill points. a) conventional, b) flat, c) long angle.

20. What applications are the following drill bits well suited to? a) high helix, b) straight flute, c) gun, d) hard steel, e) core, f) oil hole.

21. What will happen if a drill bit has unequal angles on the cutting edges/lips? What if the edges are not of equal length?

22. Why should most holes be started with a center drill?

23. What are the disadvantages of a thick web found on some drills?

24. What is the purpose of pilot holes?

25. What is the main difference between a) threading operations and tapping operations? b) boring and reaming?

26. List 5 ways work can be held in a lathe.

27. Can peripheral and face milling be done with the same cutter? How common is this?

28. Describe the steps in cutting a 3/8-12-UNC taped hole.
(ans. center drill, drill 1/4”, drill .292”, starting tap, finishing tap)

29. a) Explain the cutting mechanism of a drill bit, and b) suggest the features of a drill bit for cutting a thin piece of sheet metal.

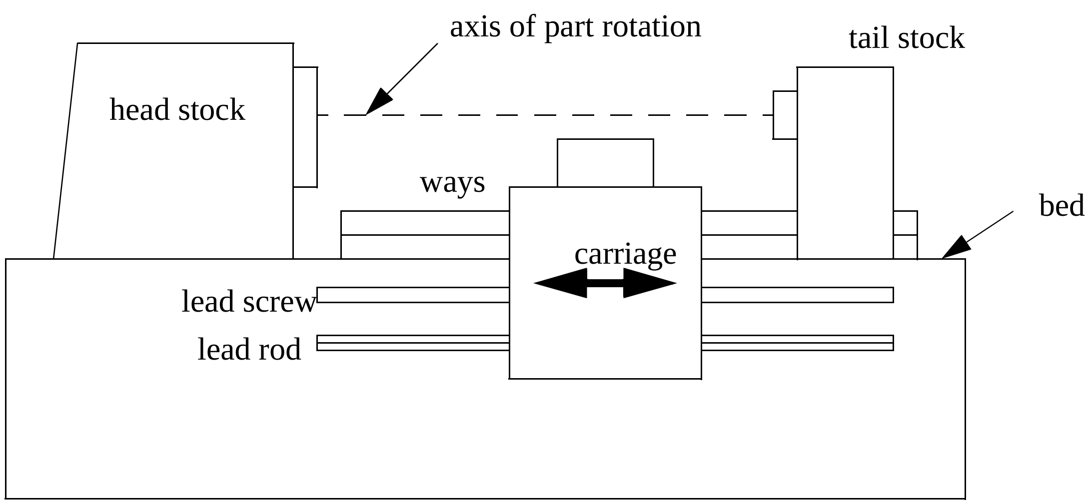
8. LATHES

• Cutting is performed in lathes by rotating the workpiece, and then holding a relatively stationary tool against it. Where the tool touches, the work is cut down in round patterns.

8.1 INTRODUCTION

• A lathe is a large machine that rotates the work, and cutting is done with a non-rotating cutting tool. The shapes cut are generally round, or helical. The tool is typically moved parallel to the axis of rotation during cutting.

• Manual lathes have the following major components,



head stock - this end of the lathe contains the driving motor and gears. Power to rotate the part is delivered from here. This typically has levers that let the speeds and feeds be set.
ways - these are hardened rails that the carriage rides on.
tail stock - this can be used to hold the other end of the part.
bed - this is a bottom pan on the lathe that catches chips, cutting fluids, etc.
carriage - this part of the lathe carries the cutting tool and moves based on the rotation of the lead screw or rod.
lead screw - a large screw with a few threads per inch used for cutting threads
lead rod - a rod with a shaft down the side used for driving normal cutting feeds.

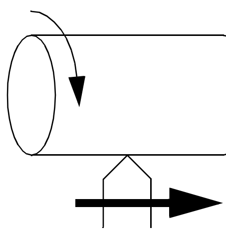
• General classifications used when describing lathes are,
  - Swing - the largest diameter of work that can be rotated.
  - Distance Between Centres - the longest length of workpiece

- Length of Bed - Related to the Distance Between Centres
- Power - The range of speeds and feeds, and the horsepower available

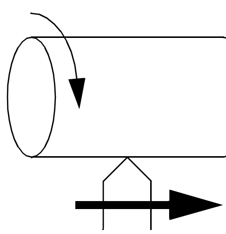
• The critical parameters on the lathe are speed of rotation (speed in RPM) and how far the tool moves across the work for each rotation (feed in IPR).

8.2 OPERATIONS ON A LATHE

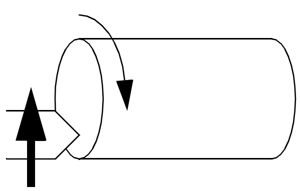
• Operations on a lathe include,



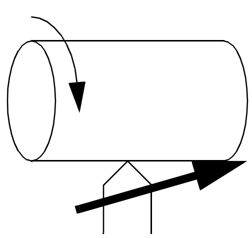
Turning - produces a smooth and straight outside radius on a part.



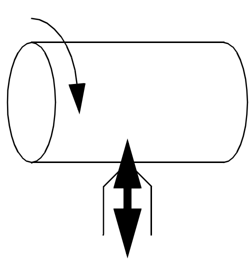
Threading - The cutting tool is moved quickly cutting threads.



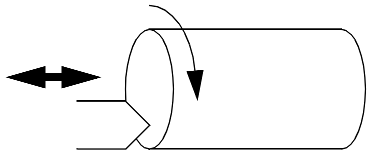
Facing - The end of the part is turned to be square.



Tapering - the tool is moves so as to cut a taper (cone shape).



Parting/Slotting/Grooving - A tool is moved in/out of the work. shallow cut will leave a formed cut, a deep cut will cut off the unsupported part.

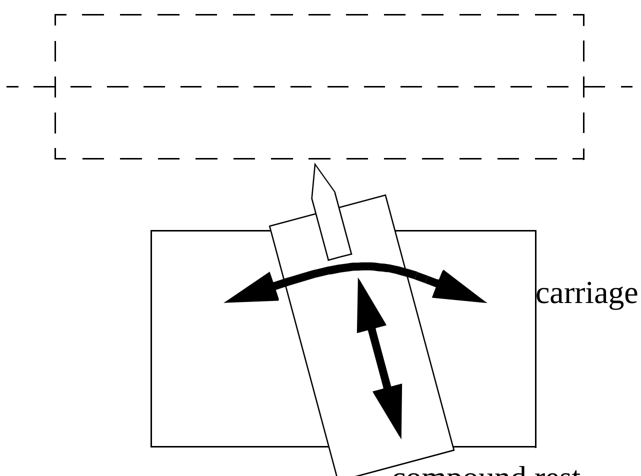


Drilling/Boring - a cutter or drill bit is pushed into the end to create an internal feature.

8.2.1 Machine tools

• There are two tool feed mechanism on most lathes. These cause the cutting tool to move when engaged.
    - The larger screw (the lead screw) will cause the lathe cutter to advance quickly. This is used for cutting screws, and for moving the tool quickly. Typical feed rates range from about 0.05” to 0.5” per revolution.
    - The small screw (the feed rod) will move the cutter slowly forward. This is largely used when doing rough cuts, or finishing operations. Typical feeds with this screw range from 0.001” to 0.010” per revolution.

• On a lathe the axial distance of the tool on the part is set by the carriage. A compound rest is used on a lathe that allows the radial tool position and orientation or the cutting edges.

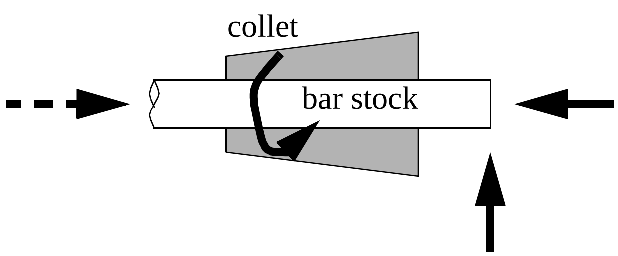


• Work is held in the lathe with a number of methods.

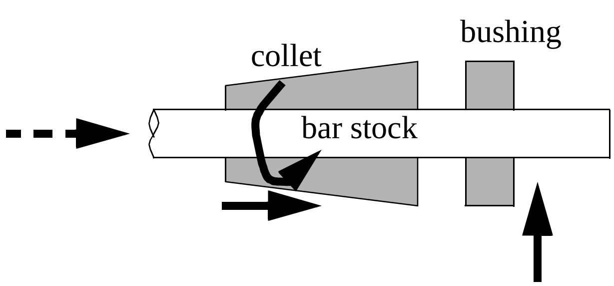
- 3 jaw self centering chuck
- 4 jaw independently adjusted chuck
- Between centres
- Face Plates
- Mandrels
- Collets
- Soft Jaws

8.2.1.1 - Production Machines

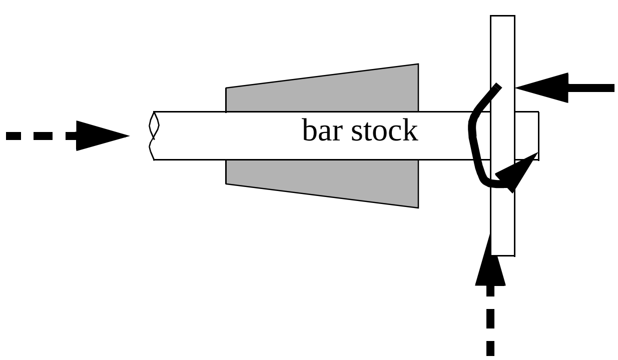
• In production there are a variety of cutting machines used to increase throughput by automatically feeding stock (through the headstock).



Collet - Stock is fed through from the back of the machine and clamped by the collet. The collet is then driven to turn the part and cutting tools cut the exposed stock and then the part is cut off, and the stock is advanced for the next part. This is the most basic process.



Sliding Headstock - In these machines the collet still grips the part, but it slowly moves forward. The cutting tools only move in a radial direction and are positioned near the bushing (it may have bearings also). Keeping the tools near the bushing reduced bending moments and allows slender parts to be cut.



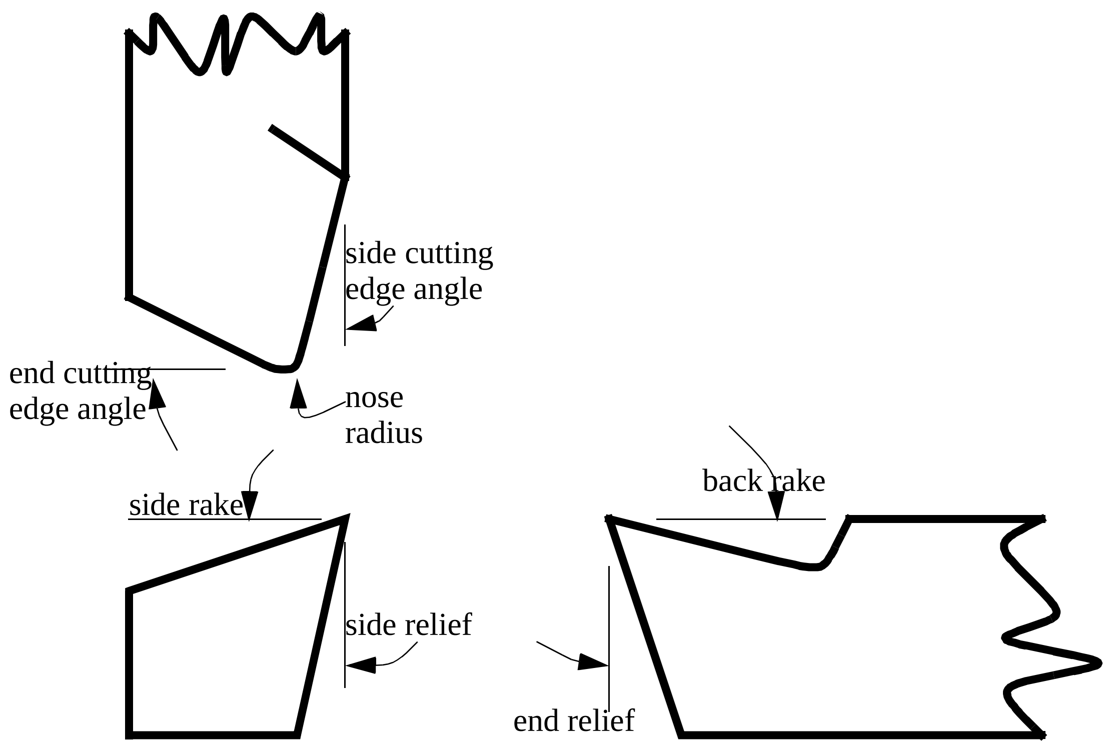
Esco - In this type of machine the bar stock is still held and advanced through a collet, but the tools rotate on a mounting assembly. The tools on the assembly can be moved in radial distances to change the profile of the part. This machine allows coiled stock to be turned and is suited to simpler parts.

• Other types of turning centers provide multiple operations on a single machine,
- Multispindle - Multiple spindles in a single machine allows parallel operations in a sin-

gle lathe. Between each operation the spindles are advanced to the next operations.
- Rotary Transfer - Large machines where parts are moved to different stations, typically over ten stations. These may have other tools such as drills mounted.
- CNC machines - These computer controlled machines are typically flexible, but a bit slower. Flexibility is enhanced by a wider variety of operations and multiple tools in the same machine.
- Cam - For high production rates, cams can be made to drive the cutting heads. Their geometry will move the tool in complex patterns.

8.3 LATHE TOOLBITS

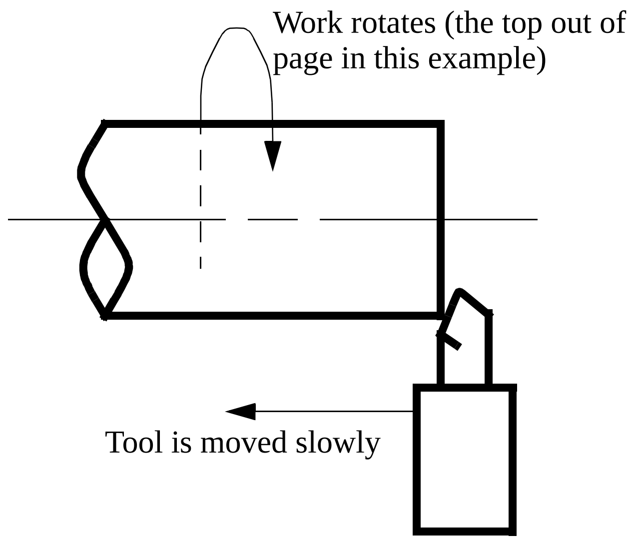
• A lathe toolbit is shown in the figure below, with a few terms defined.



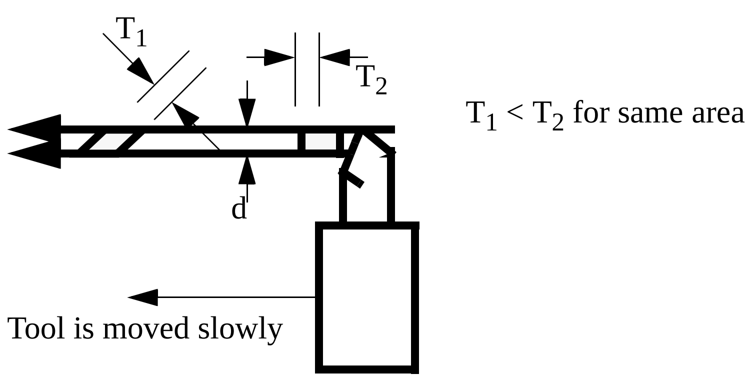
• In general, as the rake angle increases (positive), the cutting forces are reduced, the surface finish improves, and tool life increases.

• The side edge cutting angle has two effects outlined below,

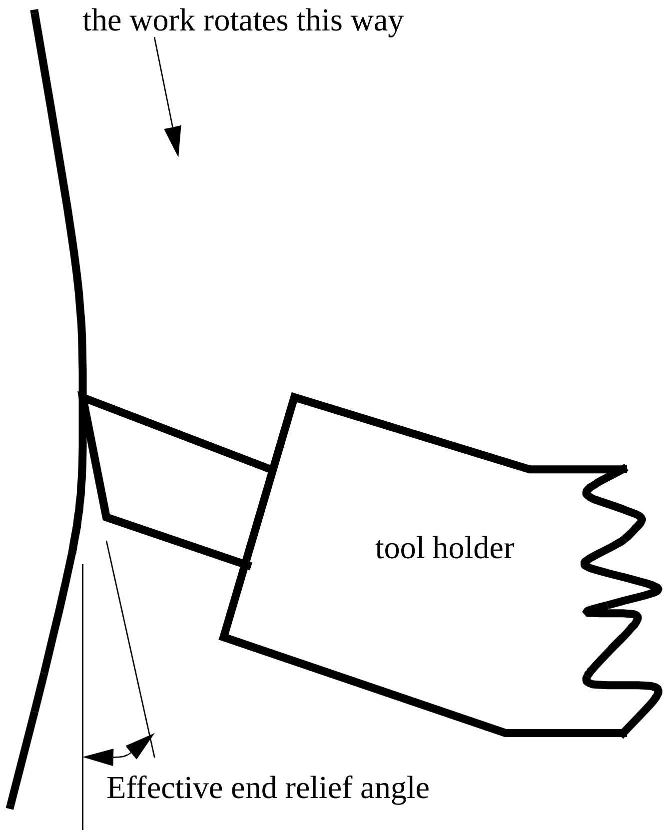
1. The angles edge allows a slow build up of cutting forces



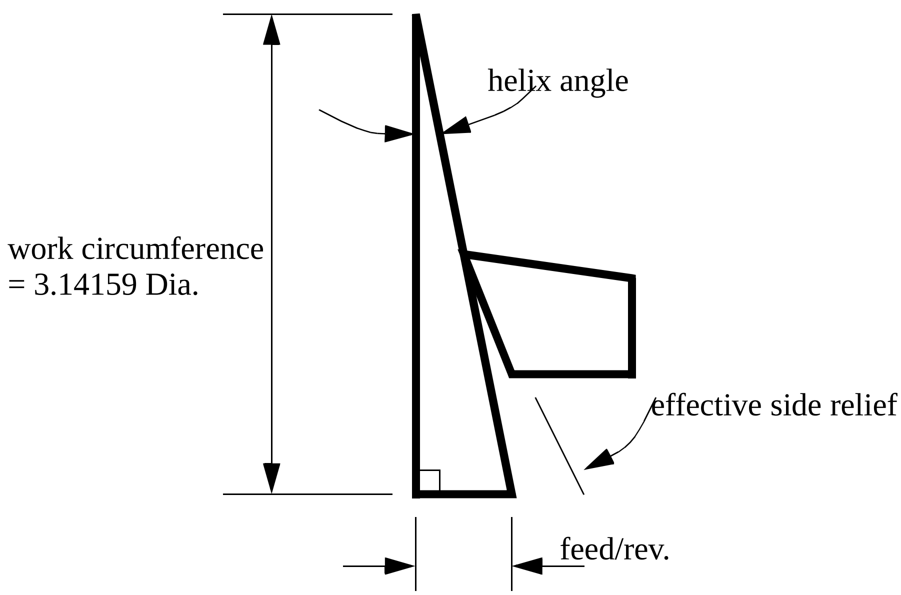
2. Increase in the side rake angle reduces the chip thickness



• The End Relief Angle prevents friction on the flank of the tool. The holder for the bit is often angled, and the end relief angle must be larger than the tool holder angle to prevent rubbing.



• The side relief angle has a function similar to the end relief, This angle must exceed the feed helix angle.



• Increasing the nose radius improves the surface finish. But this reaches a limit.

8.3.1 Thread Cutting On A Lathe

• Threads are cut using lathes by advancing the cutting tool quickly so that it cuts in a helical band. This helical band is actually a thread. The procedure calls for correct settings of the machine, and also that the helix be restarted at the same location each time.

• The basic procedure is,

1. The tool point must be ground so that it has the same angle as the thread to be cut. Typical angles are 60° for Vee threads, and 29° for ACME threads. A thread gauge can be used to measure thread angles. (also called Centre Gauge or Fish Tail Gauge).
2. The correct gear ratio is required between the machine spindle to the lead screw. This can be determined with the equation,

$$ratio = \frac{driver}{driven} = \frac{TPI_{LEADSCREW}}{TPI_{WORKPIECE}}$$

where,

$$TPI_{LEADSCREW} = \text{ the threads per inch on the lead screw (typically 4)}$$

$$TPI_{WORKPIECE} = \text{ the TPI to be cut on the workpiece}$$

For example, to cut 20 TPI we calculate,

$$ratio = \frac{4}{20} = 5\left(\frac{4}{20}\right) = \frac{20}{100}$$

The increase is made to match the number of teeth available in our lathe (these figures depend on specific machine tools).

3. The compound slide is set at half the thread angle. This is so that as multiple passes are made to cut the thread (most threads require a few passes to cut), the tool will be advanced in by the compound slide in such a way that only one face cuts. If both faces were used for cutting there would be a good chance of vibrations and chatter. For example, if a 60° thread is being cut, the compound rest is often set at 29°.
4. The cutting tool is set in the holder perpendicular to the work, and the fishtail gauge is used to check the angle of the point.
5. The In-feed is set to the surface of the part for the first pass (quite often the first pass just scratches the surface to allow visual checking of the settings). On each subsequent pass the infeed will be set closer.
6. The cross slide is set at the same location for each cutting pass. i.e., the dial setting is zero.

7. The In-feed is adjusted on the compound slide for each pass by moving it in a distance. A simple measure of this distance is,

$$\Delta_{INFEED} = \frac{0.75}{TPI}$$

************************** INCLUDE CHASING DIAL FIG 31-13

8. The chasing dial is used to restart the thread cutting in synchronization with what has been cut before. (If this step is not done properly, the notches in a thread might be cut over existing ridges - effectively cutting the entire thread flat to the bottom). The carriage of the lathe in driven across by a split nut. When the split nut is closed over the lead screw, it begins to move. It must be clamped over the lead screw when it is at the right angle. The method for doing this is with the chasing dial. The chasing dial has 16 different locations to engage at. In some cases you can engage the nut at any time, in other cases there are only a few positions to engage at. The basic rules are,

Calculate the following ratio (the previous example is used for illustration), and reduce the denominator to the smallest integer value.

$$R = \frac{TPI_{WORKPIECE}}{TPI_{LEADSCREW}} = \frac{20}{4} = \frac{5}{1}$$

Other examples could be,

$$\frac{18}{4} = \frac{9}{2}, \frac{19}{4}, \frac{7\frac{1}{2}}{4} = \frac{15}{8}, \frac{3\frac{1}{4}}{4} = \frac{13}{16}$$

Then looking at the denominator only, select the positions of the chasing dial that the carriage can be engaged at,

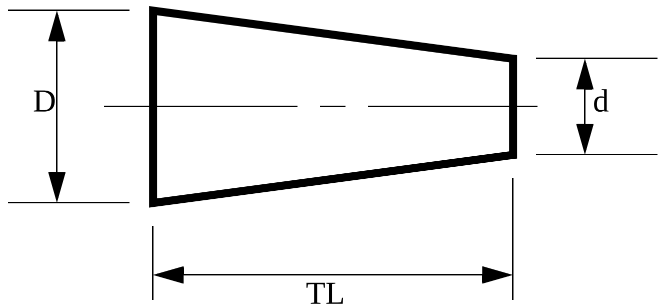
DENOMINATOR	WHEN TO ENGAGE CARRIAGE
1	close nut at any position
2	every 1/8 of dial (e.g., at any line)
4	every 1/4 of dial (e.g., at any line with number)
8	every 1/2 of dial (e.g., 1 and 3, or 2 and 4)
16	every revolution at the same place (e.g., 1)

8.3.2 Cutting Tapers

• A taper is a conical shape.

• Tapers can be cut with lathes quite easily.

• The typical measures for tapers are shown below,



where,

TL = taper length
D = the large diameter
d = the small diameter

In Imperial:

$$tpf = \frac{D - d}{TL} \times 12$$

where,

D = large diameter (in.)
d = small diameter (in.)
TL = the taper length (in.)
tpf = taper per foot (in./ft.)

In Metric:

Specified as a ratio of mm change in diameter to length in mm
For example, a 20cm long bar that changes in diameter from 3cm to 2.2cm would result in,

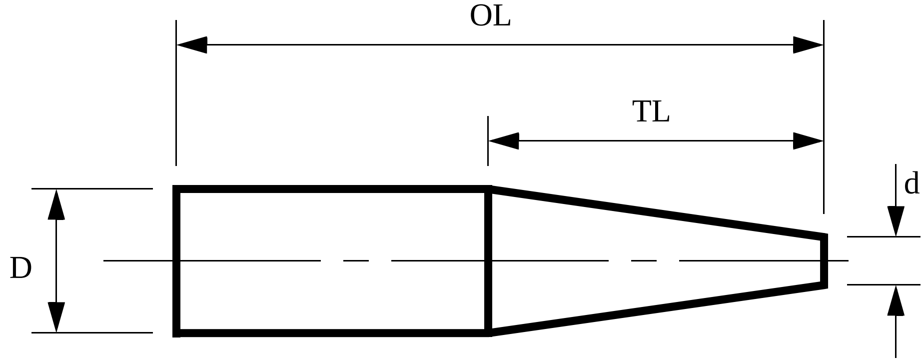
$$\Delta D : TL = (30 - 22) : 200 = 8 : 200 = 1 : 25$$

• Standard tapers include,
- Lathe-Spindle Nose - Used for alignment of hole/shaft pairs
    type D-1 (tpf = 3”)
    type L (tps = 3.5”)
- Self Holding Tapers - Used for stability
    Taper shank drills, reamers, sleeves, etc.
    Use “Morse Tapers” numbered 1 to 7

8.3.3 Turning Tapers on Lathes

• There are some common methods for turning tapers on a lathe,
- Off-setting the tail stock
- Using the compound slide
- using a taper turning attachment
- using a form tool

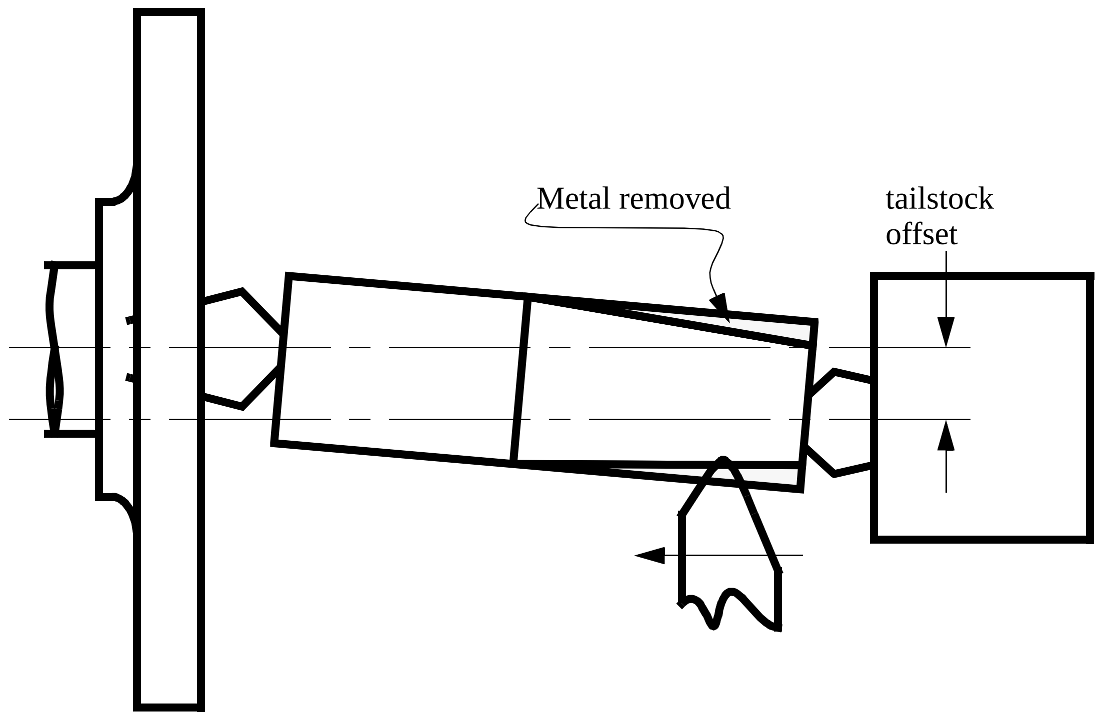
• Off-Set Tail Stock - In this method the normal rotating part of the lathe still drives the workpiece (mounted between centres), but the centre at the tailstock is offset towards/away from the cutting tool. Then, as the cutting tool passes over, the part is cut in a conical shape. The method for determining the offset distance is described below.



$$OFFSET = \frac{OL}{TL} \times \frac{(D-d)}{2} = \frac{tpf \times OL}{24}$$

where,

OL = overall length
TL = taper length
D = the large taper diameter
d = the small taper diameter
tpf = taper per foot (in.)
OFFSET = the distance to move the tailstock from the zero setting



It is necessary to measure the tailstock offset when using this method. This can be done with,

1. A scale
2. A dial indicator

This method is limited to small tapers over long lengths.

The misalignment of the centres used in this method can cause damage to the work, and to the centres.

- The Compound Slide Method - The compound slide is set to travel at half of the taper angle. The tool is then fed across the work by hand, cutting the taper as it goes.

- Taper Turning Attachment - Additional equipment is attached at the rear of the lathe. The cross slide is disconnected from the cross feed nut. The cross slide is then connected to the attachment. As the carriage is engaged, and travels along the bed, the attachment will cause the cutter to move in/out to cut the taper.

- Form Tool - This type of tool is specifically designed for one cut, at a certain taper angle. The tool is plunged at one location, and never moved along the lathe slides.

8.4 FEEDS AND SPEEDS

• If we consider the speed and feed of a lathe,
- Spindle Speed is in revolutions per minute
- Feed is in inches per revolution

• The Feed Chart is used to select the speeds and feeds of the lathe, and is often attached to the lathe near the setting levers.

• There are some simple (geometric) equations that can be listed,

$$CS = rpm \times C$$

$$C = \frac{\pi D}{12} = \frac{\pi D}{1000}$$

$$rpm = \frac{12 \times CS}{\pi \times D} = \frac{1000 \times CS}{\pi \times D}$$

imperial metric

where,

CS = cutting speed (fpm or m/s) - can be selected from tables
rpm = revolutions per minute of the machine spindle
C = circumference of the workpiece (ft. or m)
D = diameter of workpiece (in. or mm)

$$T = \frac{L}{rpm \times F}$$

$$C = T \times R$$

where,
L = length of cut (in. or mm)
F = feed rate (in./rev. or mm/rev.) - found in tables
R = Machine cost ($/min.)

• Typical cutting speeds for a high speed steel tool are, [Krar]

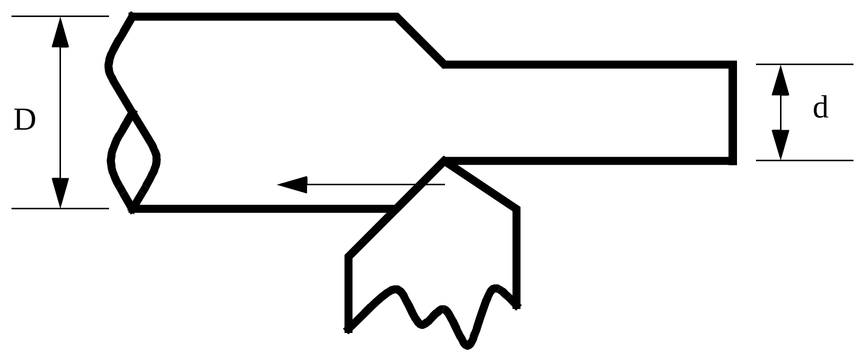
Material	Rough Cut (fpm)	Finish Cut (fpm)	Thread cut (fpm)
machine steel	90	100	35
tool steel	70	90	30
cast iron	60	80	25
bronze	90	100	25
aluminum	200	300	60

• Typical feeds when using a high speed steel tool are, [Krar]

Material	Rough Cut (in./rev.)	Finish Cut (in./rev.)
machine steel	0.010-0.020	0.003-0.010
tool steel	0.010-0.020	0.003-0.010
cast iron	0.015-0.025	0.005-0.012
bronze	0.015-0.025	0.003-0.010
aluminum	0.015-0.030	0.005-0.010

8.4.1 The mrr for Turning

• considering the parameters defined in the discussion of speeds and feeds, etc, the mrr is given below,



$$mrr = \left(\frac{\pi D^2}{4} - \frac{\pi d^2}{4}\right) \times F \times rpm$$

where,

D = diameter of workpiece before cutting
d = diameter of workpiece after cutting

8.4.2 Process Planning for Turning

• The general steps when process planning for turning external parts are,

1. Rough cuts all diameters to within 1/32” starting with the largest diameters first.
2. Rough cut all shoulders and steps to within 1/32”
3. Do special operations such as knurling and grooving
4. Cool the workpiece to get it close to the final dimension.
5. Finish turn the diameters, then the shoulders and steps
6. Deburr if necessary

• If the part is to be mounted between centres, plan should precede by,

1. cut stock that is 1/8” larger than required.
2. Put the work in the lathe, in a chuck, and face and centre drill the end.
3. reverse the pice in the chuck and face the piece to size, and centre drill.
4. Mount the work between centres

• For work to be mounted in a chuck, (implies internal features),

1. cut the stock 1/8” wider in diameter, and 1/2” longer.
2. Mount the work in the chuck with 5/16” to 3/8” inside.
3. Use a facing operation (lightly) to square the end.
4. Rough cut the external diameters, from the largest to the smallest.
5. Drill out the centre of the work using a drill chuck mounted in the tailstocks spindle. Start with a centre drill, and increase drill sizes to increase the hole.
6. Mount a boring tool to cut the internal diameter to close to the final diameter.

7. Cut any special feature now.
8. Do finish cuts on outside and inside.
9. Reverse the part in the chuck and face off the material to size. Protect the work by placing a piece of soft metal between it and the chuck.

8.5 PRACTICE PROBLEMS

1. Given that a tapered piece is to be made with the tailstock offset method, determine the taper per foot, and offset required if, you are starting with a bar of stock that is 8” long, and 1.125” in diameter, and the final taper is to be 6” long and 1” at the small end.

(ans. tpf = 0.25”, offset = 0.0833”)

2. Given the 1/2-12 UNC thread that is to be cut on the lathe,

    a) What should the gear ratio between the machine spindle and the lead screw be if the lead screw is 5 t.p.i.?
    b) What should the in-feed be for each pass?

3. Which of the following statements about lathe toolbits is correct?
    a) a small nose radius will result in a smoother surface.
    b) small relief angles will always increase friction.
    c) large rake angles will decrease cutting forces.
    d) none of the above.

(ans. c)

4. Which of the statements about lathes below is most correct?
    a) jawed chucks hold only standard sizes of pieces.
    b) mandrels hold work pieces from the outside.
    c) the chasing dial is used for measuring fine cuts.
    d) lead screws and feed rods are lathe parts

(ans. d)

5. When turning between centres a dog is required; what is a dog in this context?

(ans. it holds the work piece so that it can be driven with a face plate mounted on the lathe spindle)

6. A centre gauge (fish tail gauge) is employed in thread cutting. Suggest two uses for the gauge.

(ans. aligning a cutting tool for threads,)

7. Given an external 9/16-12-UNC thread, determined which tools would be used.

(ans. a turning tool to turn the outside diameter of 9/16”+1/12”, UNC tool to turn thread)

8. If we are rough cutting a 5” diameter bar of bronze on a lathe with a HSS tool,
   a) what speed and feed should be used?
   b) if the cut is 12” long, and will be made in two passes, how long will the operation take?
   c) if the setup time is 5 minutes, and the machine rate is $50/hr., what will the cost of the operation be?

Using the lookup tables in the notes we pick a surface cutting speed and feed.

$$D = 5in \qquad L = 12in \qquad R = 50\$/\mathrm{hr}$$

Rough

$$CS = 90\frac{ft}{min}$$

$$f = \frac{0.015 + 0.025}{2}\frac{in}{rev} = 0.02\frac{in}{rev}$$

$$rpm = \frac{12CS}{\pi D} = 68$$

$$T = \frac{L}{rpm \times f} = 17.39min$$

$$C = T \times R = \left(\frac{2(8.82) + 5}{60}\right)50 = 18.71\$$$

Finish

$$CS = 100\frac{ft}{min}$$

$$f = \frac{0.003 + 0.010}{2}\frac{in}{rev} = 0.0065\frac{in}{rev}$$

$$rpm = \frac{12CS}{\pi D} = 76$$

$$T = \frac{L}{rpm \times f} = 24.29min$$

$$C = T \times R = \left(\frac{2(24.29) + 5}{60}\right)50 = 44.65\$$$

9. List the basic steps for setting up a lathe to cut a thread on a bar of stock, assume the stock is mounted between centres already.
(ans. see thread cutting section)

10. If a taper of 1mm in 10mm is to be cut, what will the offset distance be for a 10cm part?

11. Calculate the machine tool spindle speeds for the following,
   a) turning on a lathe with a high speed steel tool in mild steel work with a diameter of 2.75”. The cutting speeds is 100 ft./min.

12. We have been given a mild steel bar that is to be turned on a lathe. It has a diameter of 14” and a length of 28”. We have been asked to make two rough passes, and one finishing pass. The tool we have selected is Carbide. When doing rough cuts we use a feed of 0.007”/rev., and for finishing cuts we use a feed of 0.004”/rev. How long will this operation take?

13. Which of the following statements about lathe toolbits is correct?
    a) a small nose radius will result in a smoother surface.
    b) small relief angles will always increase friction.
    c) large rake angles will decrease cutting forces.
    d) none of the above.

ans. C or D

14. Which of the statements about lathes below is most correct?
    a) jawed chucks hold only standard sizes of pieces.
    b) collets hold work pieces from the outside.
    c) the chasing dial is used for measuring fine cuts.
    d) lead screws and indexers are lathe parts

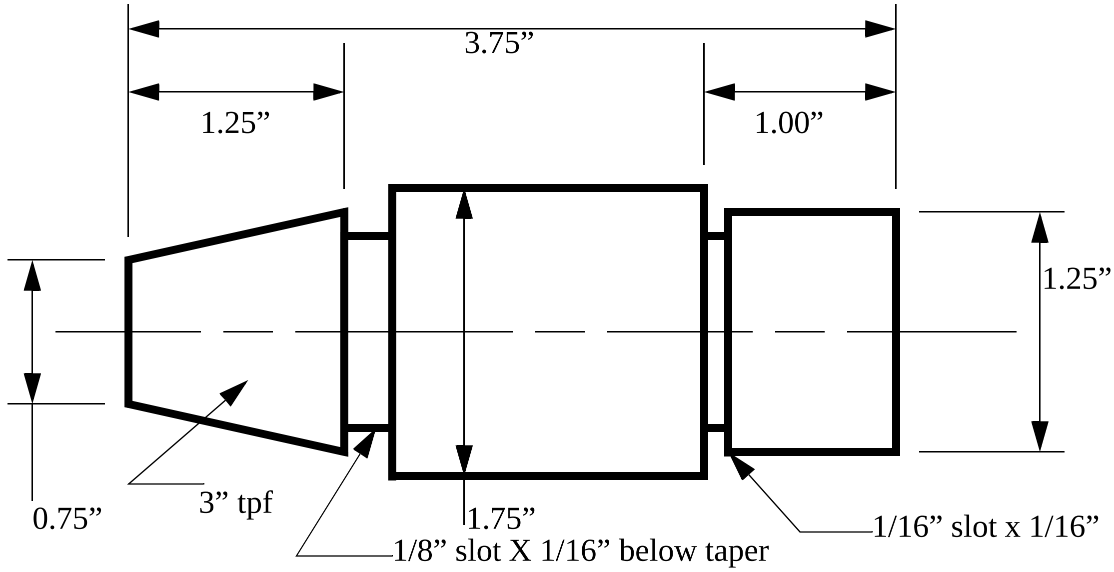
ans. B

15. Given the non-standard 3/8-19 UNC thread that is to be cut on the lathe,

    a) What should the gear ratio between the machine spindle and the lead screw be if the lead screw is 4 t.p.i.?
    b) What should the in-feed be for each pass?

ans. a) 4/19, b) 0.039

16. Develop a rough process plan for the part below by clearly listing operation steps in the correct sequence. Feeds, speeds, times and costs are not needed at this time.



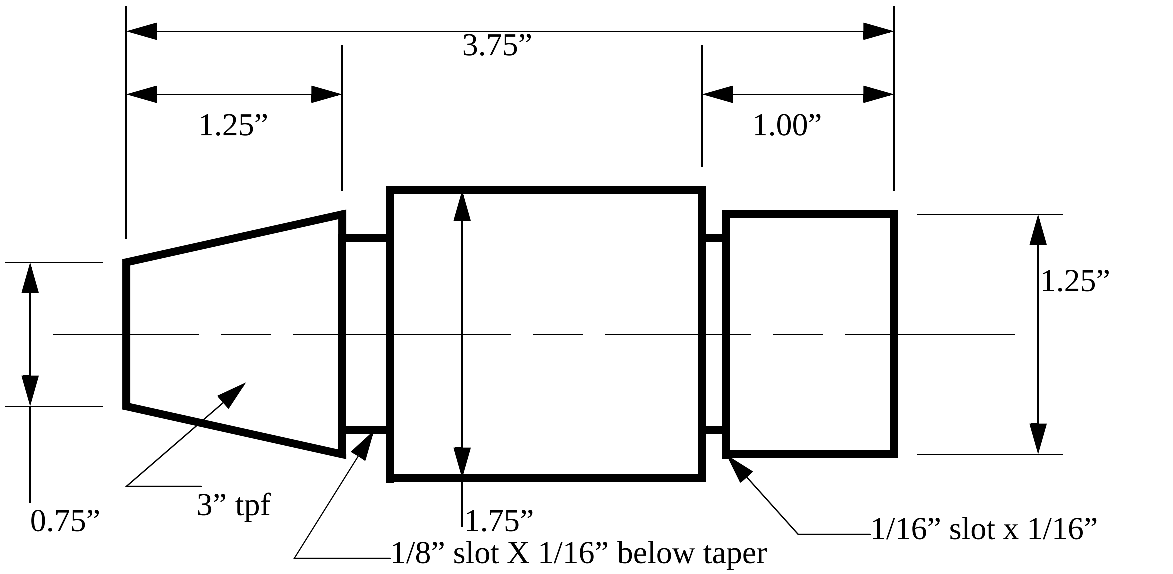
Operation Number	Operation Description
0010	Cut off 2” dia. Stock to 4”
0020	Mount in lathe chuck, face and centre drill

ans.

Operation Number	Operation Description (Note excess details given for beginners)
0010	Cut off 2” dia. Stock to 4”
0020	Mount in lathe chuck, face and center drill to 3.75” length
0030	Mount between centers
0040	Turn entire length to 1.75” dia.
0050	Cut slot with form tool 1” from end to 1/16” depth
0060	Turn one end down to 1.25”dia. for 15/16”
0070	Reverse part in centers (cover finished end with soft metal)
0080	Cut 1/8” by 1/16” slot
0090	Turn taper with taper turning attachment
0100	Return tailstock to normal position
0110	Deburr and inspect
	*Note: the implied tolerances +/- 0.005 would not require cooling

17. The aluminum component below is to be turned on a lathe using a HSS tool. Develop a process plan, including offset for the taper, speeds, feeds, etc. Put the process plan in a list similar to the format shown. Assume a cost of $45.00/hr. for the lathe, and $25.00/hr. for all other

pieces of equipment. State all assumption clearly, and justify numbers in the process plan with calculations or references.



Operation Number	Operation Description	Time	Cost
0010	Cut off Stock to 4”	6 min.	$5.00
0020	Mount in lathe chuck, face and centre drill	12 min.	$9.00

18. On a lathe toolbit what are the functions of, a) the side relief angle, b) end relief angle, c) back rake, d) side rake angle, nose radius.

19. What applications are large positive rake angles for? negative rake angles?

20. What is the difference between end and face milling?

21. What RPM should be used to rough cut a cast iron piece with a 3” dia. with a high speed steel tool. What RPM should be used for a similar workpiece of plain carbon steel? What RPM should be used for the two materials if finishing cuts are being made?

22. Calculate the time required to machine a 2” dia. copper rod that is to be turned for a length of 10”.

23. What are rough and finish turning operations used for?

24. What are two methods for cutting stepped shoulders on a lathe?

25. Explain the difference between self holding and steep tapers using the coefficient of friction.

26. Find the tpf and tailstock offset for tapers on the following work.

a) D=1.5”, d=1.25”, TL=4”, OL=8”

27. convert a metric taper of 1:50 to a tpf. Convert a 1”tpf to metric.

28. Define the terms, fit, tolerance, allowance, limits, clearance, press fit, precision.

29. For a 1”-8-NC thread find the minimum and maximum diameters and minimum width of the toolbit point.

30. Describe the differences in speeds, feeds and depths of cuts for roughing and finishing cuts.

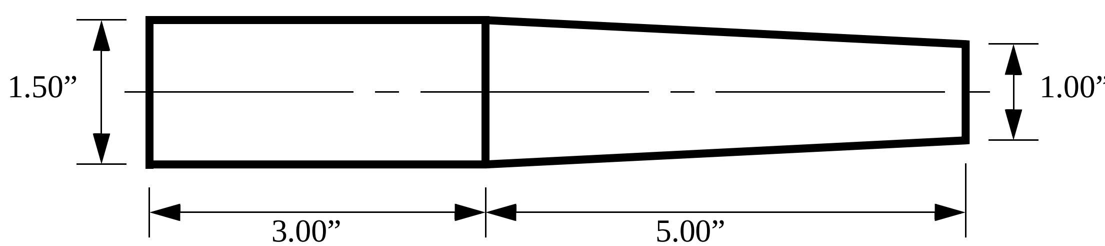
31. What types of chips are desirable when setting up automated cutting processes?

32. Compare the time to cut a work piece using a high speed steel tool and a carbide tool. The 4” dia. aluminum work is to be rough turned over a length of 14”.

33. What operations can be performed on a lathe?

34. How are the parameters different for a lathe when turning, as opposed to finishing?

35. A taper is to be cut on the aluminum part below. Indicate how far the tailstock should be offset and the speed and feed settings for the lathe.



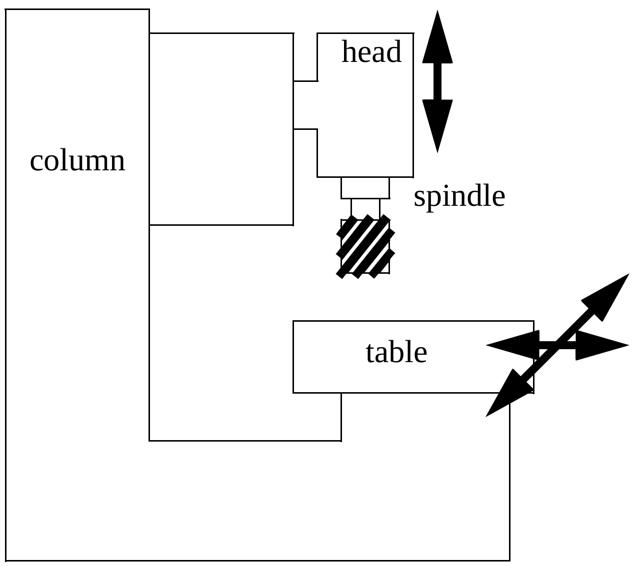
(ans. offset=0.4”, feed 0.005-0.010”, speed 760RPM)

9. MILLING

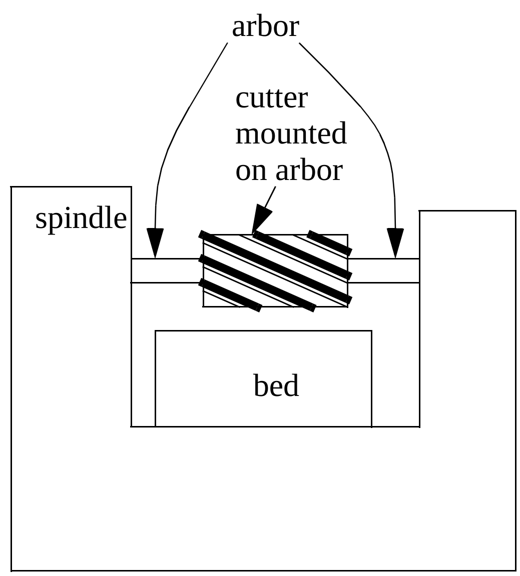
• Milling machines typically have a rotating cutting tool mounted in a spindle. The work is mounted on a bed, and then either the spindle, or bed is moved. Cutting is done with different parts of the milling tool, as will be described later.

9.1 INTRODUCTION

• Some basic types of milling machines include,
  - Knee and Column
    - vertical
    - horizontal
    - horizontal with vertical head attachment
    - universal (table rotates in plan view) and is used for helical milling
  - Ram & Turret - Light weight machine tool with slotter on one end of turret. No power feeds.
  - Special Purpose - For production usage. Usually more rigid construction.



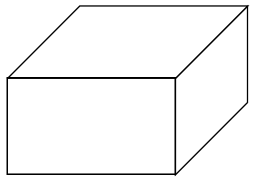
spindle mill



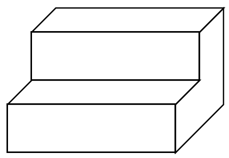
arbor mill

9.1.1 Types of Milling Operations

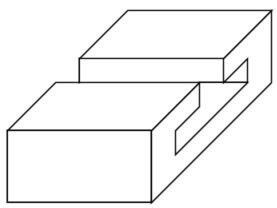
• Typical operations re pictured below



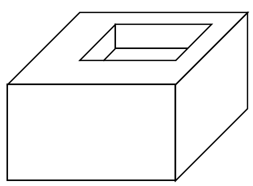
Face - cut a face flat



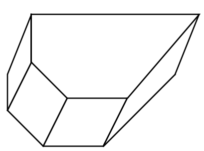
Step



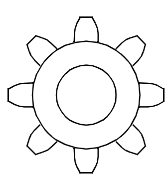
Slots



Pockets/contours



Angles



Gear Teeth

9.1.1.1 - Arbor Milling

• The advantages of arbor milling are,
  - The cutter is held more rigidly on the spindle nose
  - There is less variation in the arbor torque
  - The teeth responsible for surface finish do not encounter the hard mill scale
  - Lower power requirements
  - Flatter work surface finish.

• For straddle milling
  - Two similar side and face cutters are mounted on the same arbor, with spacers to separate them.
  - This allows two sides of a part to be cut in a single pass.

• For Gang milling
  - Many dissimilar cutters are mounted on the same arbor at the same time.
  - When the work is passed under the cutter, multiple cuts are made in a single pass, reducing alignment problems, and decreasing operation time.

9.1.2 Milling Cutters

• The family milling cutters include a number of basic operations, but in general they will cut with some combination of the end and/or the sides.

• The basic types include,
  - End Mills - The face and sides at the bottom end of this tool are used for plunge cutting (two flutes) and side and end cuts (four flute).
  - Plain - These mills are used to cut with the sides only. They are generally mounted on an arbor.
  - Side or Side & Face -
  - Face - This cutter is held on a spindle nose.
  - Shell and adapter -
  - Form -
  - T-Slot, Dovetail, Woodruff -
  - Slitting Saws -

9.1.3 Milling Cutting Mechanism

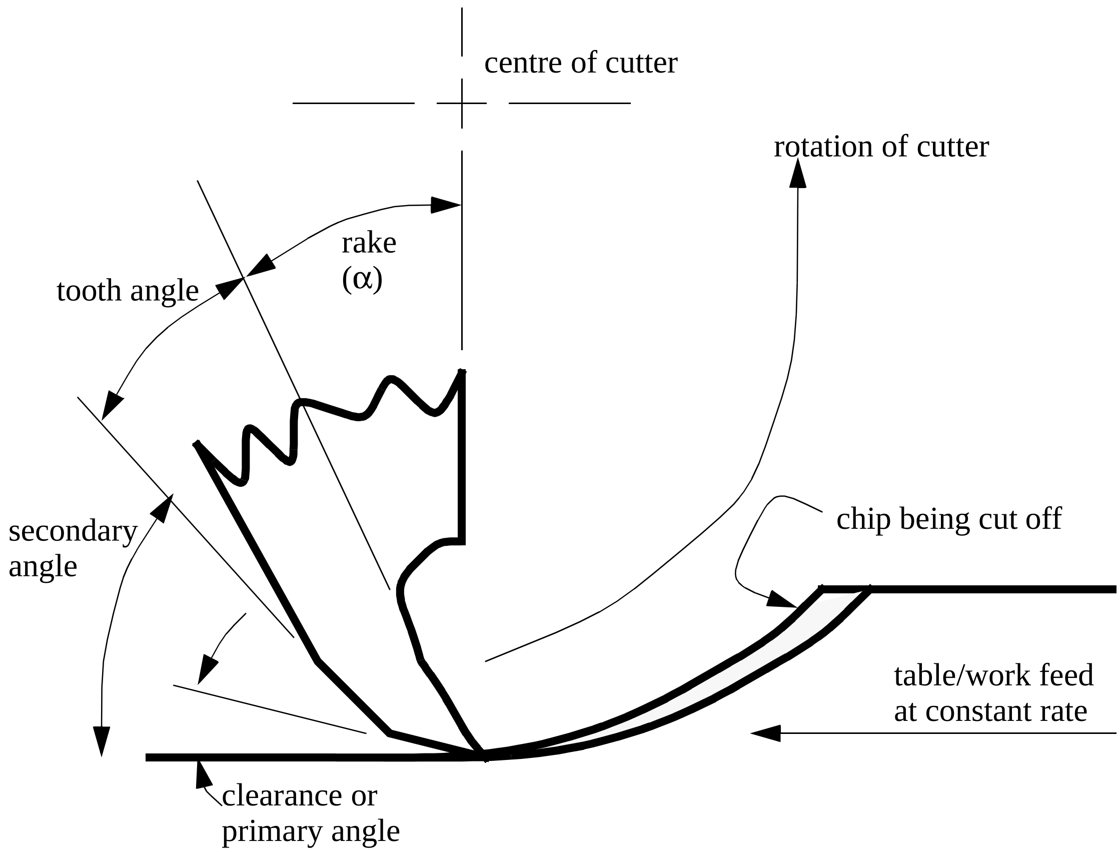
• In milling each tooth on a tool removes part of the stock in the form of a chip.

• There are two types of cutting actions,

Peripheral - The teeth at the periphery do the cutting

Face - The teeth on the face of the cutter remove metal.

• The basic interface between tool and work is pictured below. This shows a peripheral milling tooth.

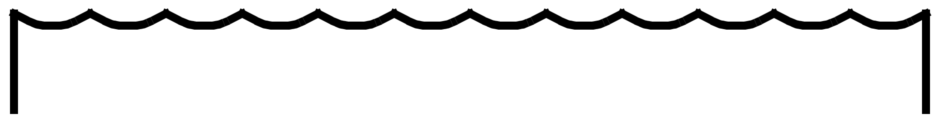


9.1.3.1 - Up-Cut Milling

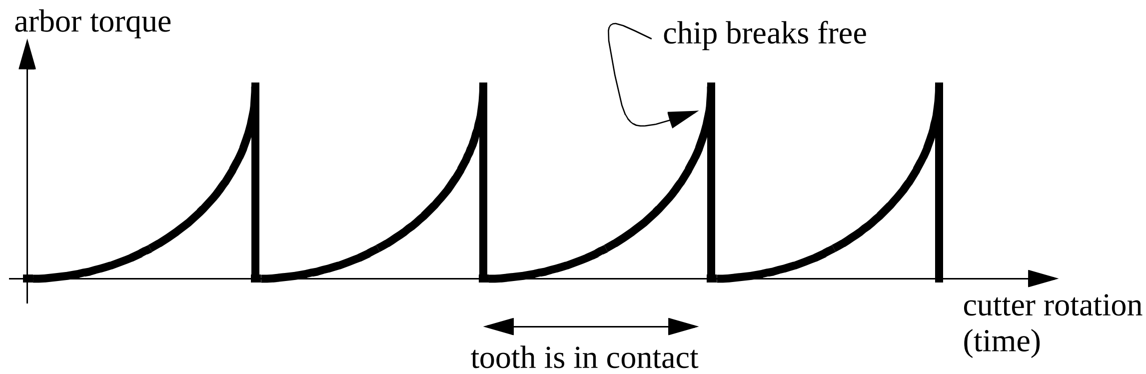
• The milling method shown above is called up-cut (or conventional) milling. In this case the table is moving towards the cutter, opposing the cutter direction. The basic steps of chip cutting here are,

1. As the tooth makes contact with the surface, the tooth begins to push down. As the tooth continues to turn, it reaches a point at which the pressure has built up to a high level, and the tooth begin to dig in.
2. As the tooth starts to dig, it cuts down, and the metal chip begins to shear off.
3. The tooth continues to cut the chip off, until it reaches the surface of the material. At this point the chip breaks free, and the cutting forces drop to zero.

• Because the cutter does not start to cut when it makes contact, and because the advance moves high points past the cutter contact, the surface has a natural waviness.



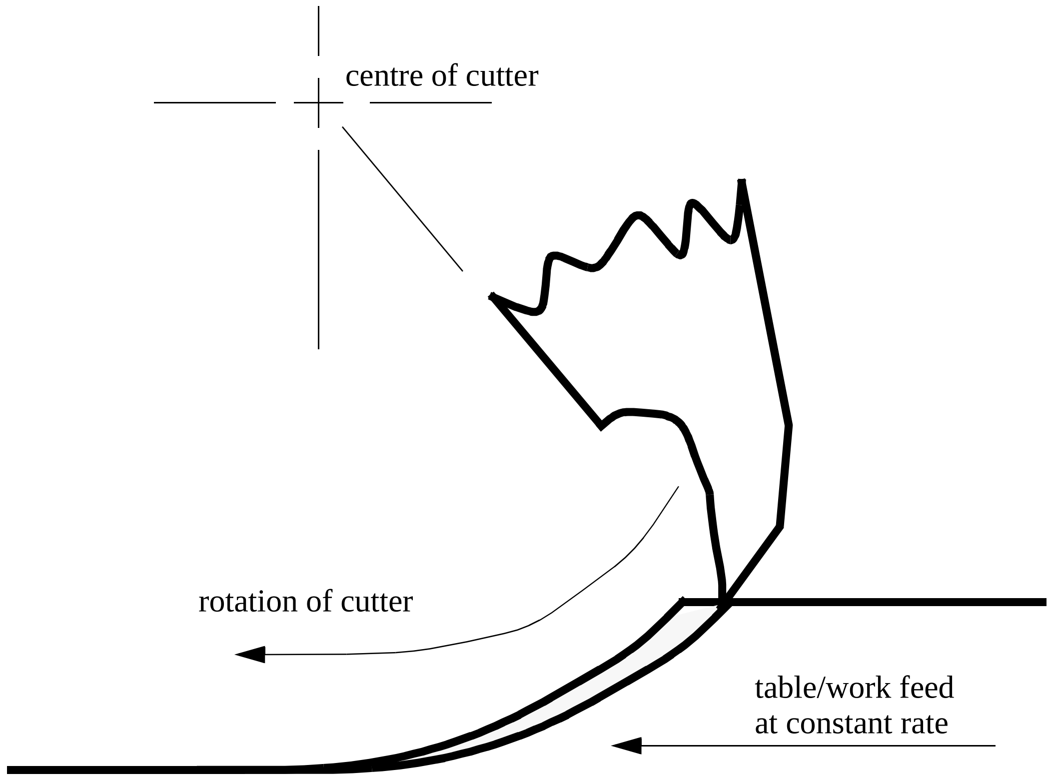
• If a cutter has straight flutes, then a torque profile for it might look like,



• The peak arbor torque can be smoothed out by using helical cutting blades, so that there is always a cutter in contact at any one time.

9.1.3.2 - Down-Cut Milling

• When the cutter rotation is in the same direction as the motion of the work being fed, it is referred to a Down-cut, or climb milling.



• When this cutter makes contact with the work, it must begin cutting at the maximum torque. As a result, a back-lash eliminator must be used to take play out of the system.

• This method has advantages,
  - The cutter forces are directed into the table, which reduces fixture forces, and allows thinner workpieces
  - There is less radial pressure on the arbor
  - Better surface finishes obtained because there is no “dig-in”

9.2 FEEDS AND SPEEDS

• Milling is somewhat different than drilling and turning,

$$CS = rpm \times C$$

$$C = \frac{\pi D}{12} = \frac{\pi D}{1000}$$

$$rpm = \frac{12 \times CS}{\pi \times D} = \frac{1000 \times CS}{\pi \times D}$$

imperial metric

where,

CS = cutting speed (fpm or m/s) - can be selected from tables
rpm = revolutions per minute of the machine spindle
C = circumference of the cutter (ft. or m)
D = diameter of the cutter (in. or mm)

$$F = fpt \times \#t \times rpm$$

where,

F = feed rate (in./min.) - this is independent of the spindle rpm
fpt = feed per tooth - found in tables
#t = number of teeth on a particular tool

$$T = \frac{L}{F} = \frac{L}{rpm \times F}$$

$$C = T \times R$$

where,

L = length of cut (in. or mm)
R = Machine cost ($/min.)

• Typical speeds are, [Krar]

Work Material	HSS tool (fpm)	carbide tool (fpm)
machine steel	70-100	150-250
tool steel	60-70	125-200
cast iron	50-80	125-200
bronze	65-120	200-400
aluminum	500-1000	1000-2000

• Typical feed per tooth values for HSS cutters, [Krar]

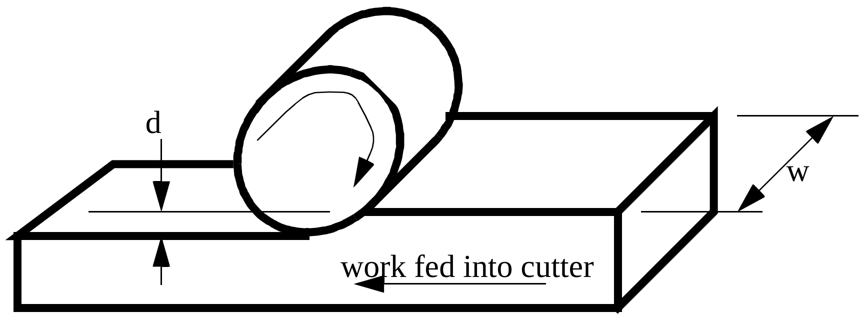
Material	face mill (in.)	helical mill (in.)	slot/side mill (in.)	end mill (in.)	form cut (in.)	circular saws (in.)
aluminum	0.022	0.018	0.013	0.011	0.007	0.005
brass/bronze (medium)	0.014	0.011	0.008	0.007	0.004	0.003
cast iron (medium)	0.013	0.010	0.007	0.007	0.004	0.003
machine steel	0.012	0.010	0.007	0.006	0.004	0.003
tool steel (medium)	0.010	0.008	0.006	0.005	0.003	0.003
stainless steel	0.006	0.005	0.004	0.003	0.002	0.002

• Typical feed per tooth values for cemented carbide (tipped) cutters, [Krar]

Material	face mill (in.)	helical mill (in.)	slot/side mill (in.)	end mill (in.)	form cut (in.)	circular saws (in.)
aluminum	0.020	0.016	0.012	0.010	0.006	0.005
brass/bronze (medium)	0.012	0.010	0.007	0.006	0.004	0.003
cast iron (medium)	0.016	0.013	0.010	0.008	0.005	0.004
machine steel	0.016	0.013	0.009	0.008	0.005	0.004
tool steel (medium)	0.014	0.011	0.008	0.007	0.004	0.004
stainless steel	0.010	0.008	0.006	0.005	0.003	0.003

9.2.1 The mrr for Milling

• considering the parameters defined in the discussion of speeds and feeds, etc, the mrr is given below,



$$mrr = w \times d \times F$$

where,

w = width of cut
d = depth of cut

9.2.2 Process Planning for Prismatic Parts

• The basic steps are,
1. Cut off the stock slightly larger than required.
2. Cut the basic outside diameter to size using a milling machine.
3. Lay out the basic features of the parts (in manual setups, this involves coating the surface with a blue stain, this is then cut and marked).
4. Use a bandsaw to rough cut the work.
5. On the mill, cut steps, radii, angles, grooves, etc.
6. Lay out the holes to be drilled, and then drill them.
7. Ream holes as required
8. Grind any surfaces that require it. Ground surfaces should generally have 0.010”

9.2.3 Indexing

• It may sometimes become necessary to rotate parts on a milling machine, beyond the rotation offered in some beds (e.g. Universal Milling Machine).

• Some of the applications that require this capability are milling of,
  - polygons,
  - splines
  - gears,
  - cams
  - spirals

• This method can be done with a dividing head. This is basically a worm gear unit. As the crank is turned, the cylindrical gear will drive the round gear. This will result in an apparatus that takes large motions in the crank, and results in small rotations of the work. When coupled with a scale of some description this becomes very accurate.

• If a worm wheel has 40 teeth, each rotation of the crank will result in a rotation of 40/360 degrees, or 1/40th of a rotation. This means the rotation is 40:1.

****************************** INCLUDE FIGURES OF INDEXING HEAD

• There are two methods of indexing,
  - Direct Indexing - A notched plate is located so that the crank shaft can be fixed at set positions (notches).
  - Simple Indexing - Work is rotated by turning a crank. The crank is finally positioned using a plate with holes, and a sector arm. (The sector arm is used to count off the divisions on the plates)

• An example of the calculations involved is, Say that we want to mill a polygon on 11 sides (i.e., 1/11th of a circle).

First, we will assume that we have a worm ratio of 40:1, and that we are using a Brown and Sharp #2 plate.

Next, we will calculate the fraction of the indexed plate to be covered,

$$INDEX = \left(\frac{40}{1}\right)\left(\frac{1}{11}\right) = \frac{40}{11} = 3\frac{7}{11}$$

So, we must turn the crank handle 3 times, plus a bit more. Next we must determine which ring of index holes to use, and how many to count ahead by.

We can do this by looking at the remainder (7/11) and taking the denominator (11). Next we look at the counts available for the Brown and Sharp #2 plate (i.e., 21, 23, 27, 29, 31, 33), and from this we will notice that 33 is a multiple of 11. Therefore we can compute the number of divisions required with,

$$holes = 33\left(\frac{7}{11}\right) = 21$$

Therefore in total, we must advance the crank 3 full rotations, and 21 holes (in the ring of 33) to rotate 1/11th of a circle.

• Another example of indexing considers a rotation of 50 degrees,

First we will calculate the total indexing required,

$$INDEX = \left(\frac{40}{1}\right)\left(\frac{50}{360}\right) = \frac{2000}{360} = \frac{50}{9} = 5\frac{5}{9}$$

Therefore there are 5 full rotations of the indexing wheel required. Next we look at the list of indexing plates. Assume we are using the Cincinnati Standards Plates, we should look for the ring that has lowest number of index holes and is a multiple of 9. This would be 54 on the other side. Therefore we would advance the sector arm by,

$$holes = 54\left(\frac{5}{9}\right) = 30$$

• Differential indexing - is sometimes required to move plates both forward and backward part of a turn to obtain correct spacing. i.e., output shaft through gear train drives the index plate. XXXXXXXXXXXXXXXXXX

• Helical milling - the machine table is rotated through a helix angle. The machine lead screw drives the dividing head. Work is rotated while the machine table feeds. XXXXXXXXXXXXXXXX

• CAM Milling - requires a milling machine with a rotating vertical head. The dividing head is driven by the machine lead screw.

9.3 PRACTICE PROBLEMS

1. A 2” diameter milling cutter with 8 teeth has been selected. What is the table feed if we are milling at 80 ft./min. with a tooth load of 0.004”/tooth?

2. Calculate the machine tool spindle speeds for the following,
    a) milling with a 3/4” high speed steel cutter in tool steel work. The CS is 60 ft./min.
    b) milling with a 150mm diameter tungsten carbide tipped face cutter in stainless steel work. The CS is 65 m/min.

3. You are given a block of aluminum (5” by 5” by 5”) and you must mill off a 1/16” layer. Using the tables for speeds and feeds, and using the other details provided below, determine a cost for the operation.

    • Milling cutter- high speed steel
        - diameter 2”
        - 10 teeth with a tooth load of 0.004” per tooth
        - cost for the machine is $20.00 per hours

ans. This cut is more than a finishing cut.

We can assume this is a light rough cut or heavy finishing cut. The cutter type will be assumed to be a face mill. Because the part width is 5" and the cutter is 2" we will need three passes to cut the part.

$$D = 2in \qquad \#t = 10 \qquad fpt = 0.004 \qquad CS = \frac{500 + 1000}{2} = 750\text{fpm}$$

$$R = 20\$/\text{hr}$$

$$rpm = \frac{12 \times CS}{\pi \times D} = \frac{12(750)}{\pi 2} = 1432$$

$$F = fpt \times \#t \times rpm = (0.004)(10)(1432) = 57\text{ipm}$$

$$L_{pass} = 5in + D \qquad L = 3L_{pass} = 3(5+2) = 21in$$

$$T = \frac{L}{F} = \frac{21in}{57ipm} = 0.37min$$

$$C = T \times R = \left(\frac{0.37}{60}\right)(20) = 0.12\$$$

4. Which of the following statements is true for milling?
   a) milling cutters can cut with the face and peripheral teeth.
   b) the cutting edge moves opposite to the direction used in lathes.
   c) indexing is used to cut rounded surfaces.
   d) none of the above.

5. What are the advantages of upcut and downcut milling?

ans. Upcut - lower tool impact forces
Upcut - loose work is safer
Downcut - pushes work into table
Downcut - better surface finish

6. Which of the following statements is true for milling?
   a) milling cutters can cut with the face and not the peripheral teeth.
   b) the cutting edge moves opposite to the direction used in lathes.
   c) indexing is only used to cut rounded surfaces.
   d) none of the above.

ans. D

7. Given a 3” dia. 8 tooth fly cutter, with carbide cutting points, and a steel work piece, recommend, a) RPM, b) feed.

8. Given a 6” dia. high speed steel arbor mill with 10 teeth, that will be cutting cast iron work, recommend, a) RPM, feed.

9. Calculate the indexing required when would be cutting a gear with 36 teeth? Use one of the Brown and Sharp indexing plates.

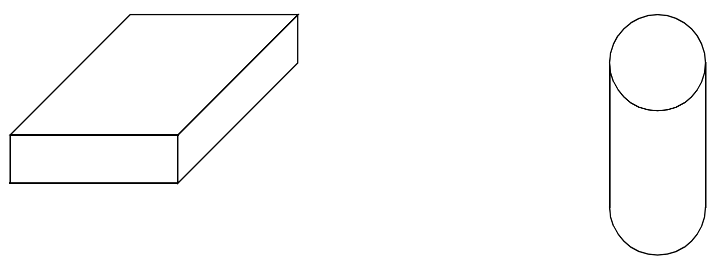
10. Determine the angular indexing required (on Brown and Sharp, and Cincinatti Standard plates) if we want an angle of 23°30’.

10. GRINDING

• Grinding has two main uses,
- as a surface finishing process for flat or cylindrical features that have already been cut.
- to cut complex surfaces with high tolerances or hard materials.

• The basic process involves an abrasive wheel spinning at high speed that is brought into contact with the work surface, thus giving a smooth finish.

10.1 OPERATIONS



Surface Finish

Formed Grooves

Internal (rounds)

10.2 MACHINE TYPES

• Typical categories of grinders include,
Surface

Cylindrical
Internal
Center
Centerless
Jig

10.2.1 Surface

• Surface grinders have a few basic types,
  - Horizontal Spindle with Reciprocating Table
  - Horizontal Spindle with Rotary Table
  - Vertical Spindle with Rotary Table
  - Vertical Spindle with Reciprocating Table

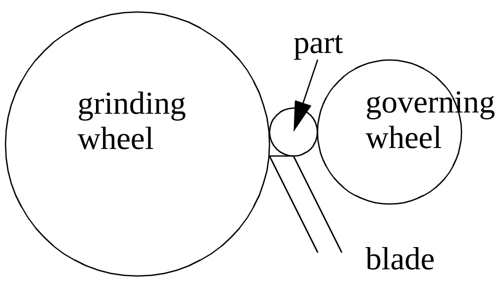
10.2.2 Center

• With centers parts are mounted so that they may rotate about fixed centers and then ground externally.

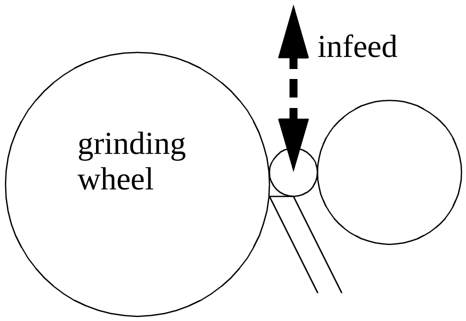
10.2.3 Centerless

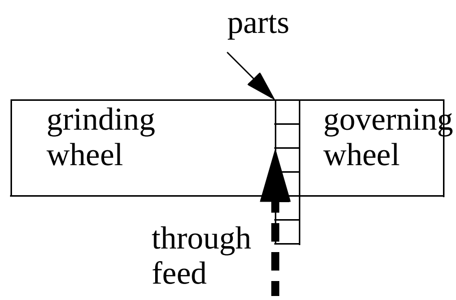
• Centerless grinding is popular as a high speed, low cost operation.

• In this operation there is a grinding wheel and a governing wheel. The part sits between the wheels and is ground by the grinding wheel. The governing wheel acts to slow the rotation of the part so that it does not spin at the same speed as the grinding wheel and reduce the surface speed of the grinding operation.



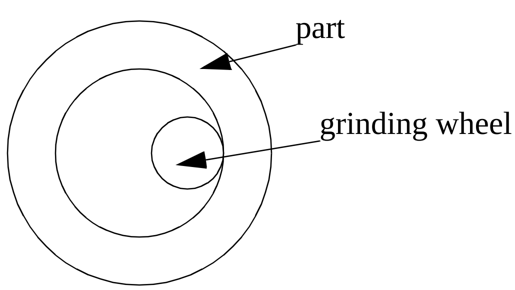
• If the part has a uniform cross section through feed grinding can be used. Otherwise infeed grinding will have to be used. For infeed grinding the parts are placed between the wheels, ground, and then pulled out. Through feed grinding has the parts move in a steady flow between the wheel.





10.2.4 Internal

• Internal grinding is similar to other forms of rotational grinding, except that as the part rotates the internal features are ground by a smaller wheel.



• Using a smaller wheel requires higher grinding speed which increases the challenge of this process.

10.3 GRINDING WHEELS

• The wheels are typically made with a bonded abrasive.

• common abrasives used are,
  Aluminum oxide
  Silicon carbide

• Grain size is typically from 6 to 600.

• The bonding mechanisms used commonly are,
  - vitrified
  - resinoid
  - rubber
  - shellac
  - silicate

• The Grade of the wheel is a measure of the ability to retain grit. If a wheel is Grade A it is soft, if it is Grade Z, it is very hard.

• The wheels are also given a structure number. 1 indicates a dense structure, whereas, 15 indicates an open structure.

• Loading of a wheel refers to the embedding of swarf in the voids.

• Glazing occurs when the grit has dulled, but is still bonded to the surface.

• Grinding wheels should undergo a dressing process.

• Many grinding wheels are shaped. This shaping is done while the wheel in the machine using diamond, or other hard shaping tools.

10.3.1 Operation Parameters

• The wheel can be made to act soft by increasing work speed, and decreasing wheel speed. The wheel can be made to act hard by reversing the parameters.

• Typical operation parameters are a depth per pass.

materials	Depth per pass (in)
softer plastics	0.005 to 0.0005
aluminum	0.003 to 0.001
ductile cast iron	0.003 to 0.001
mild steel	0.003 to 0.001
brass	0.003 to 0.0005
stainless steel	0.001 to 0.0005

• The wheel normally turns to give a CS of 3500 to 6000 fpm and wheels range from diameters of a few inches to a few feet.

• The table feed is 80-350 fpm for finishing passes. Up to 1000 is reasonable.

• For surface grinding

$$T = N\left(\frac{L}{F}\right) \qquad N = \left(\frac{W}{w-O}\right)\left(\frac{t}{d}\right)$$

where,

W = width of work
w = width of wheel
O = overlap per pass
L = length of pass
F = feed rate
N = number of passes
T = time for operations
d = depth of cut
t = thickness per pass

10.4 PRACTICE PROBLEMS

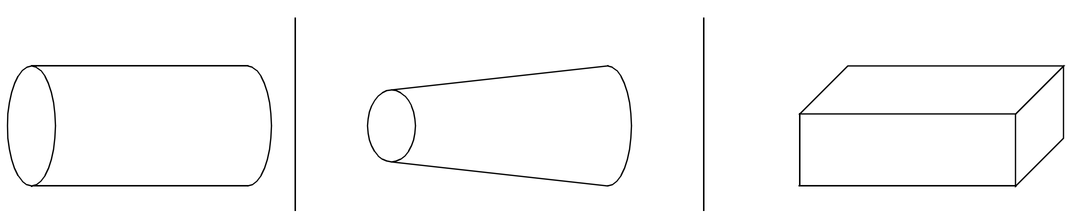
1. Why would we use grinding on a part instead of turning?

ans.
- higher dimensional tolerances
- higher quality surface finishes
- hard materials

2. Describe the basic mechanism of grinding including cutting and chip removal.

3. Why is a high grinding feed and speed problematic?

4. What type of grinding is suited to the outside surfaces for the parts below.



11. SURFACES

• No surface is perfectly smooth, but the better the surface quality, the longer a product generally lasts, and the better is performs.

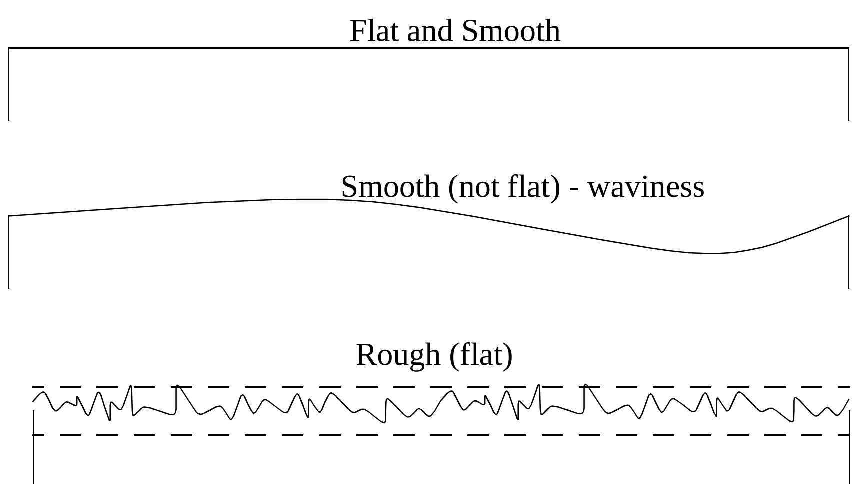
• Surface texture can be difficult to analyze quantitatively. Two surfaces may be entirely different, yet still provide the same CLA (R_a) value.

• Recent developments in production technique, and metrology equipment have made it possible to specify and measure surface quality.

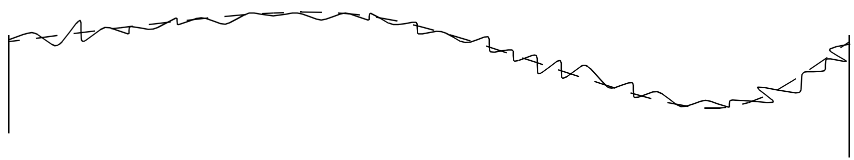
• There are standards, such as the CSA B95 1962.

• Surface Quality can be important when dealing with,
  - lubrication - small indentations can hold lubricant
  - resistant to wear - smoother surfaces wear less
  - tool life - rough surfaces will correlate to shorter tool life
  - fatigue/stress raisers -
  - corrosion - smoother surfaces easier to clean, less surface area to erode
  - noise reduction - smooth surfaces make less noise when rubbing, for example meshing gears.
  - fit - pressure seals could leak through pits

• Surface geometry can be quantified a few different ways.



• Real surfaces are rarely so flat, or smooth, but most commonly a combination of the two.

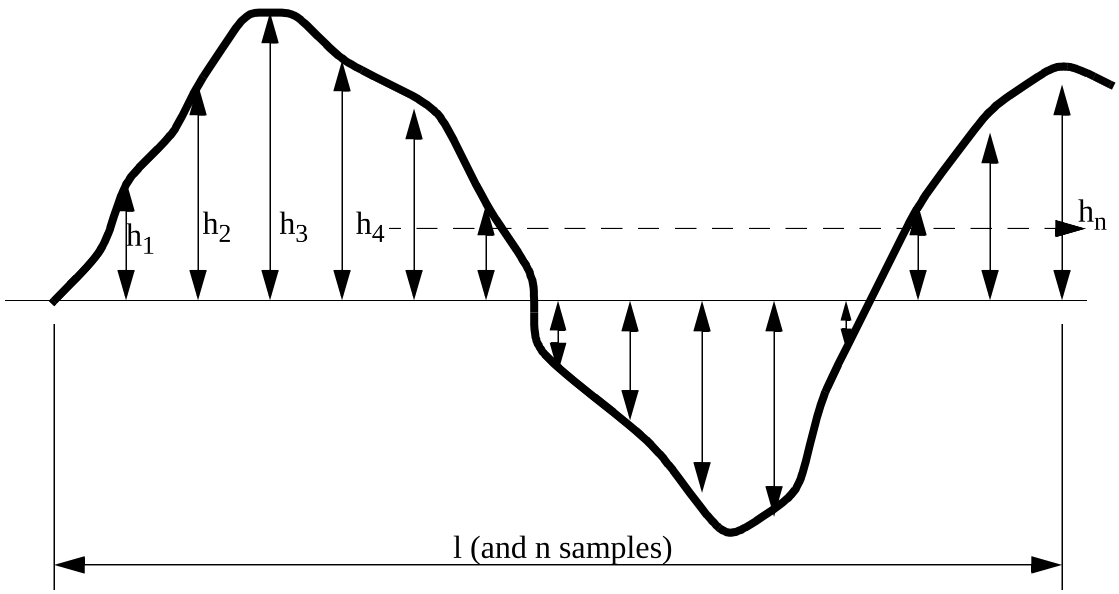


• Some other terms of interest in surface measurement,
- Surface texture - all of the details that make up a surface, including roughness, waviness, scratches, etc.
- Lay - the direction of the roughness on a newly manufactured surface. The roughest profile will be perpendicular to the lay.
- Flaws - small scratches, cracks, inclusions, etc.
- Cutoff - a value selected to be less than the waviness, but greater than the roughness length. This is controlled using electrical or digital filters. Typical values might be; 0.010”, 0.030”, 0.100”

11.1 MEASURES OF ROUGHNESS

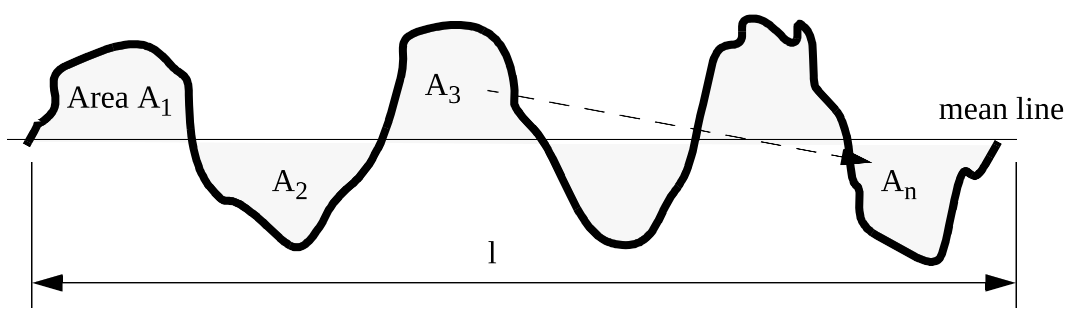
• A simple measure of roughness is the average area per unit length that is off the centre line (mean). We will call this the Centre Line Average (CLA), or Arithmetic Average (R_a), the units are μinches.

• To calculate the roughness using samples at evenly spaced positions,



$$CLA = R_a = \frac{\sum h}{n} = \frac{h_1 + h_2 + \ldots + h_n}{l}$$

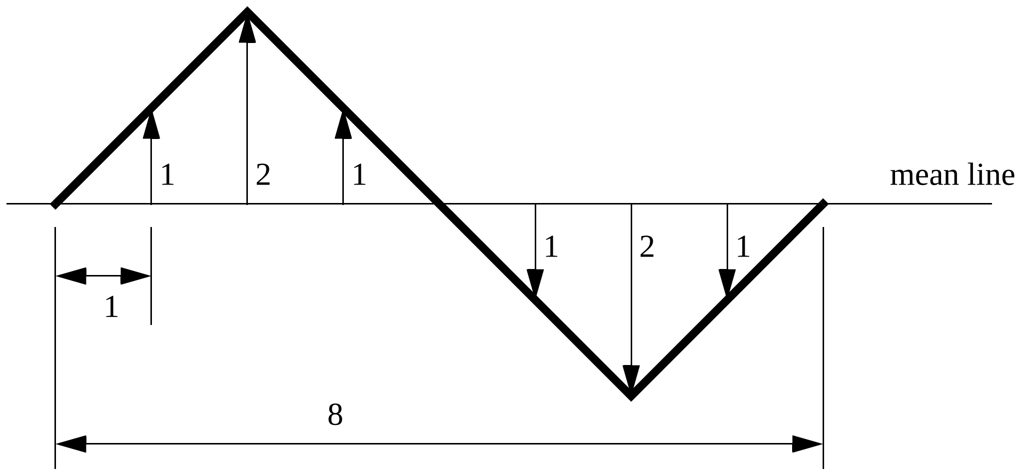
• The roughness can also be calculated by area,



$$CLA = R_a = \frac{\sum A}{l} = \frac{A_1 + A_2 + \ldots + A_n}{l}$$

• In both cases the mean line is located so the sum of areas above the line is equal to the sum of areas bellow the line.

• As an example we can examine a surface that has a triangular profile,



We can find the surface roughness using heights,

$$CLA = R_a = \frac{\sum h}{n} = \frac{1 + 2 + 1 + 0 + 1 + 2 + 1 + 0}{8} = 1$$

We can also find the surface areas using areas,

$$CLA = R_a = \frac{\sum A}{l} = \frac{4 + 4}{8} = 1$$

Note the results are the same with both methods. These numbers may vary significantly if the height method does not take enough samples for a rougher surface texture.

A secondary measure of interest is,

Full Texture Height is 2 - (-2) = 4
Full Texture Height/R_a ratio is 4:1

- One of the instruments that we will use is the Surfcom. If we were to have obtained the graph above from this device, we would have to use the following formula to determine the true values,

$$CLA = R_a = \frac{\sum A \times 10^{-6}}{l \times \text{ vertical magnification}} \mu\text{in.}$$

measured on trace

11.2 METHODS OF MEASURING SURFACE ROUGHNESS

• There are a number of useful techniques for measuring surface roughness,
  - observation and touch - the human finger is very perceptive to surface roughness
  - stylus based equipment - very common
  - interferometry - uses light wave interference patterns (discussed later)

11.2.1 Observation Methods

• Human perception is highly relative. In other words, without something to compare to, you will not be certain about what you are feeling.

• To give the human tester a reference for what they are touching, commercial sets of standards are available.

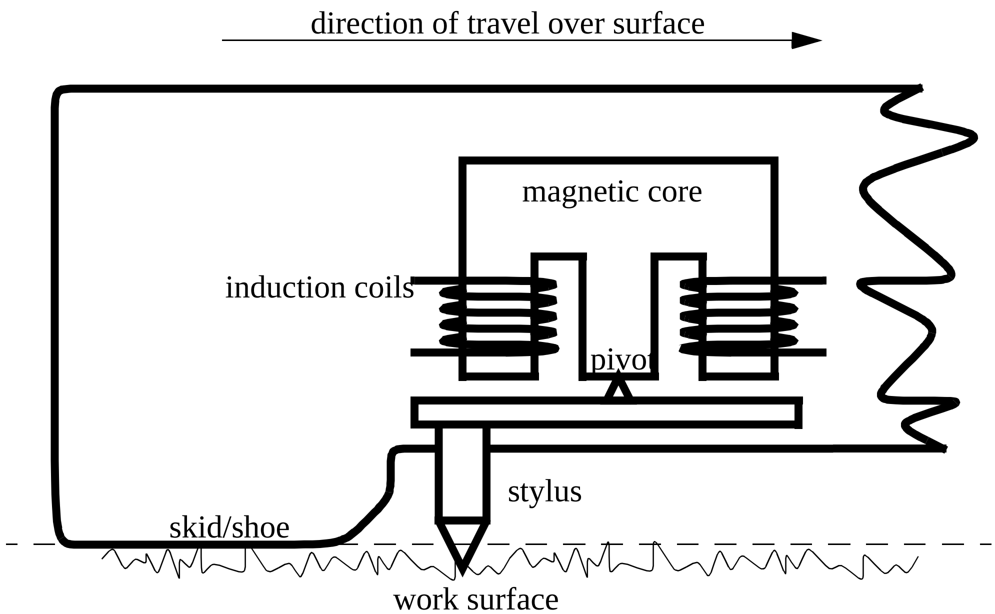
• Comparison should be made against matched identical processes.

• One method of note is the finger nail assessment of roughness and touch method used for draw dies in the auto industry.

11.2.2 Stylus Equipment

• One example of this is the Brown & Sharpe Surfcom unit.

• Basically this technique uses a stylus that tracks small changes in surface height, and a skid that follows large changes in surface height. The use of the two together reduces the effects of non-flat surfaces on the surface roughness measurement. The relative motion between the skid and the stylus is measured with a magnetic circuit and induction coils.

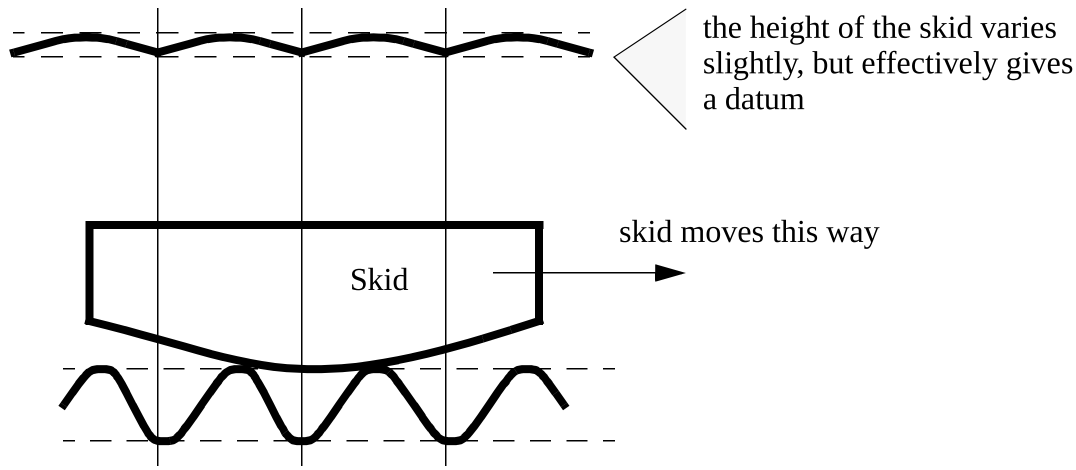


• The actual apparatus uses the apparatus hooked to other instrumentation. The induction coils drive amplifiers, and other signal conditioning hardware. The then amplified signal is used to drive a recorder that shows stylus position, and a digital readout that displays the CLA/Ra value.

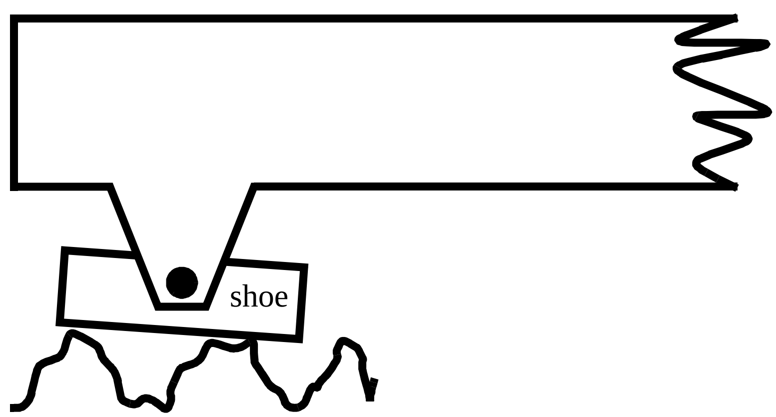
• The paper chart that is recorded is magnified in height by 100000:1, and in length by 82:1 to make the scale suitable to the human eye.

• The datum that the stylus position should be compared to can be one of three,
  - Skid - can be used for regular frequency roughness
  - Shoe - can be used for irregular frequency roughness
  - Independent - can use an optical flat

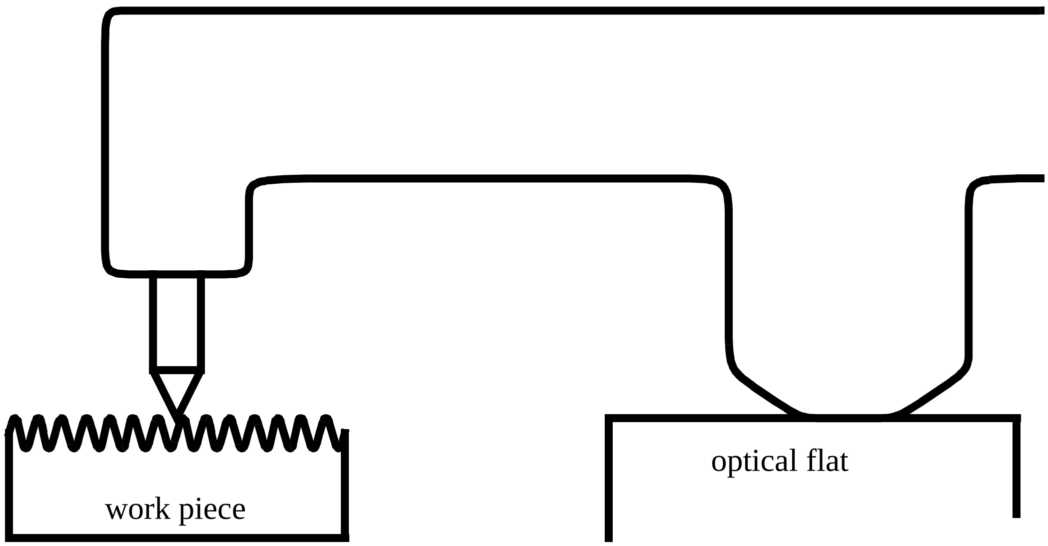
Skid - used for regular frequencies, and very common.



Flat Shoe: Used for surfaces with irregular frequencies

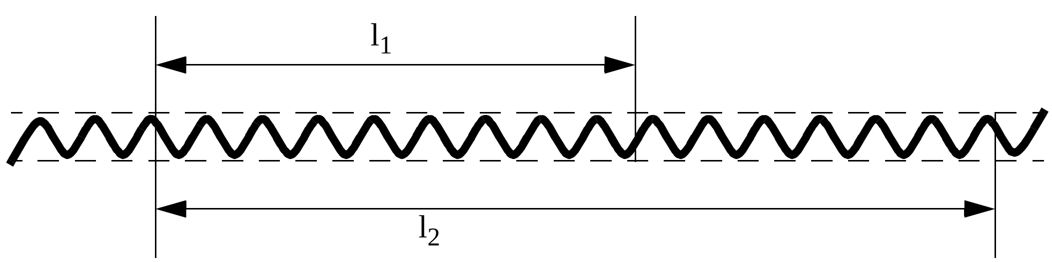


Independent Datum - a separate datum is used for the reference datum.
This may be a good application for a laboratory.

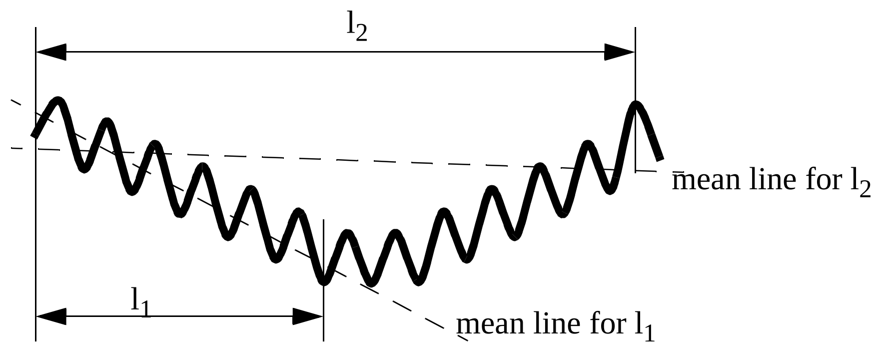


• Where the scan is stopped might influence the Ra value. This is especially true if the surface texture varies within a very small section of the surface. For example,

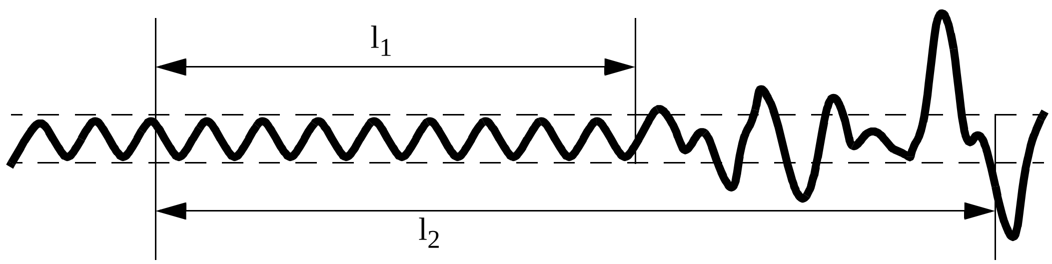
CASE 1: Measurement of l_1, or l_2 would yield the same R_a values, or very close.



CASE 2: The datum changes when the longer sample is taken, thus changing the mean line, and the R_a value also.



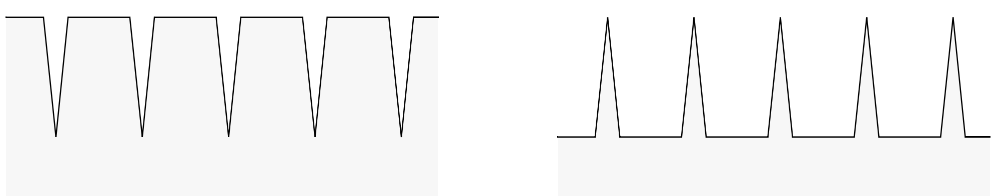
CASE 3: The surface frequency.amplitude changes over the length of the surface



• In both cases 2 and 3 above, R_a would be higher over the longer sample (l_2) than over the shorter sample (l_1).

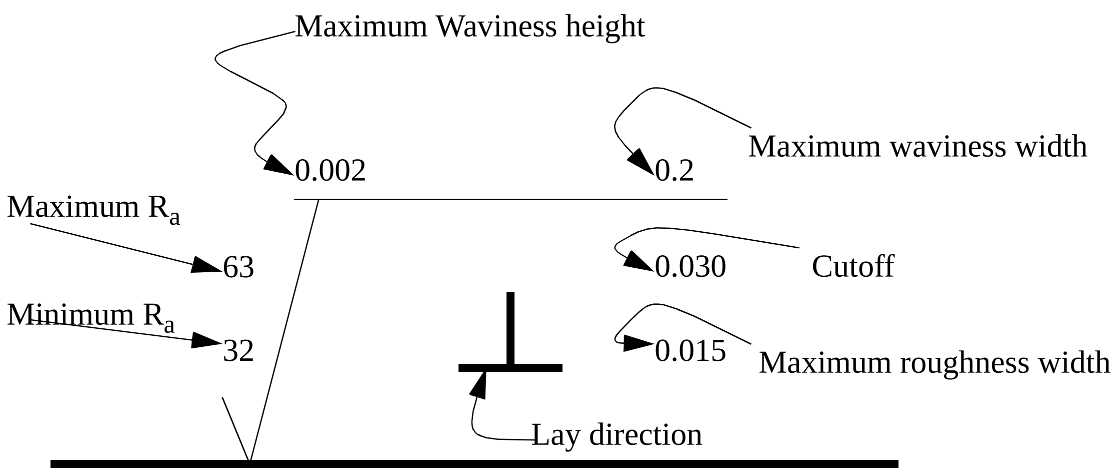
• The bearing surface that the skid/shoe runs on might also have an effected on the measurement.

Both of the two surface profiles shown below would result in the same R_a values



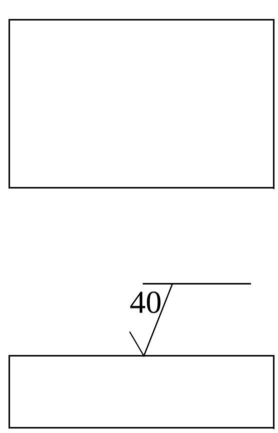
11.2.3 Specifications on Drawings

• The following specification symbol can be used on drawings to specify surface textures desired on a completed part,

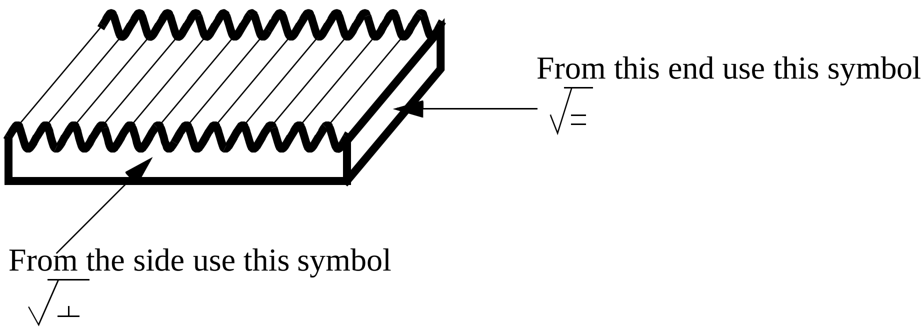


Waviness height - the distance from a peak to a valley
Waviness width - the distance between peaks or valleys
Roughness width cutoff - a value greater than the maximum roughness width that is the largest separation of surface irregularities included in the measurements. Typical values are (0.003", 0.010", 0.030", 0.100", 0.300")
Lay - the direction the roughness pattern should follow

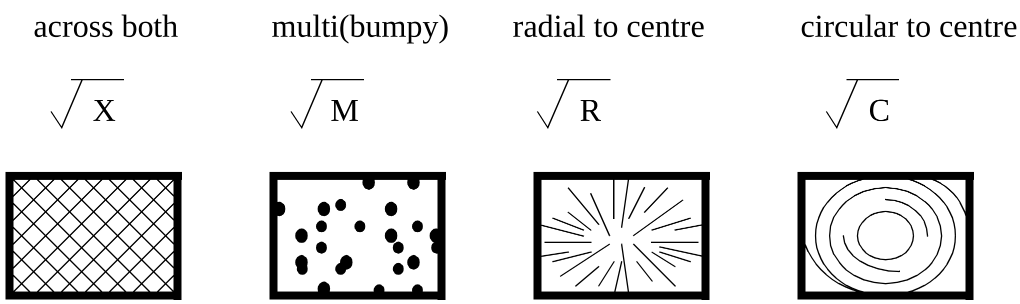
• The example below shows an upper limit of 40 micro in. roughness



• The symbol below can specify how the roughness is to lay,



Other Symbols are,



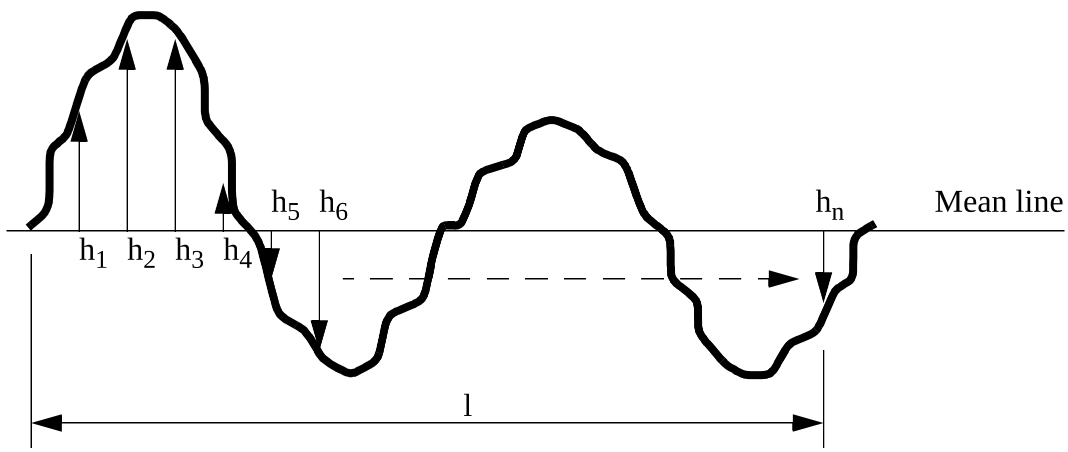
• Standards CLA/R_a values used on drawings are: 1, 2, 4, 8, 16, 32, 63, 125, 250, 500 and 1000 μin.

• Stylus travel is perpendicular to the lay specified.

• These symbols can be related to the newer GD&T symbols

11.3 OTHER SYSTEMS

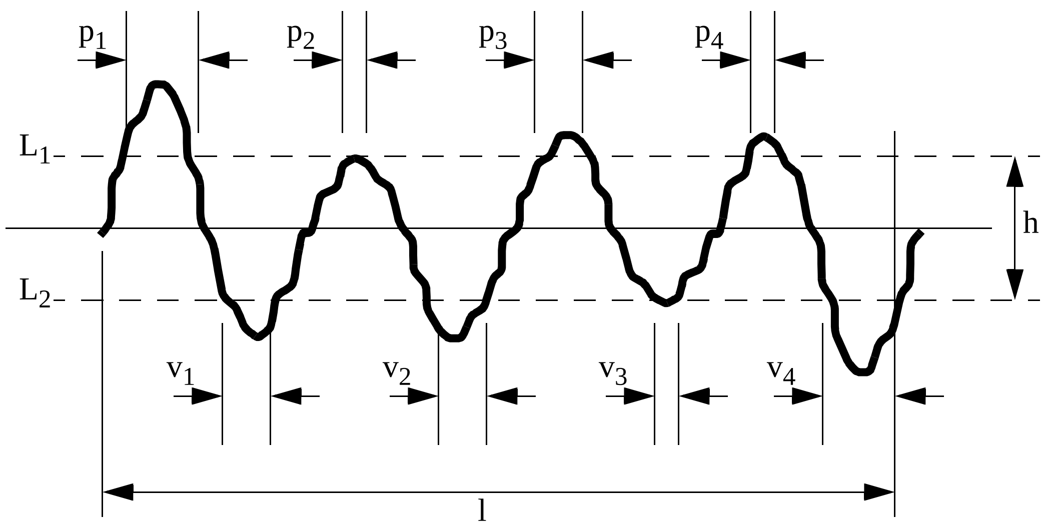
• The Root Means Squared (RMS) System (also known as R_q) is not commonly used in Canada,



$$RMS = R_q = \sqrt{\frac{h_1^2 + h_2^2 + h_3^2 + \ldots + h_n^2}{n}}$$

**Note: This value is typically 11% higher than CLA or R_a

- The Peak to Valley method cuts the peaks off the wave, and then uses the band between to determine the roughness. This method is not commonly used in Canada.

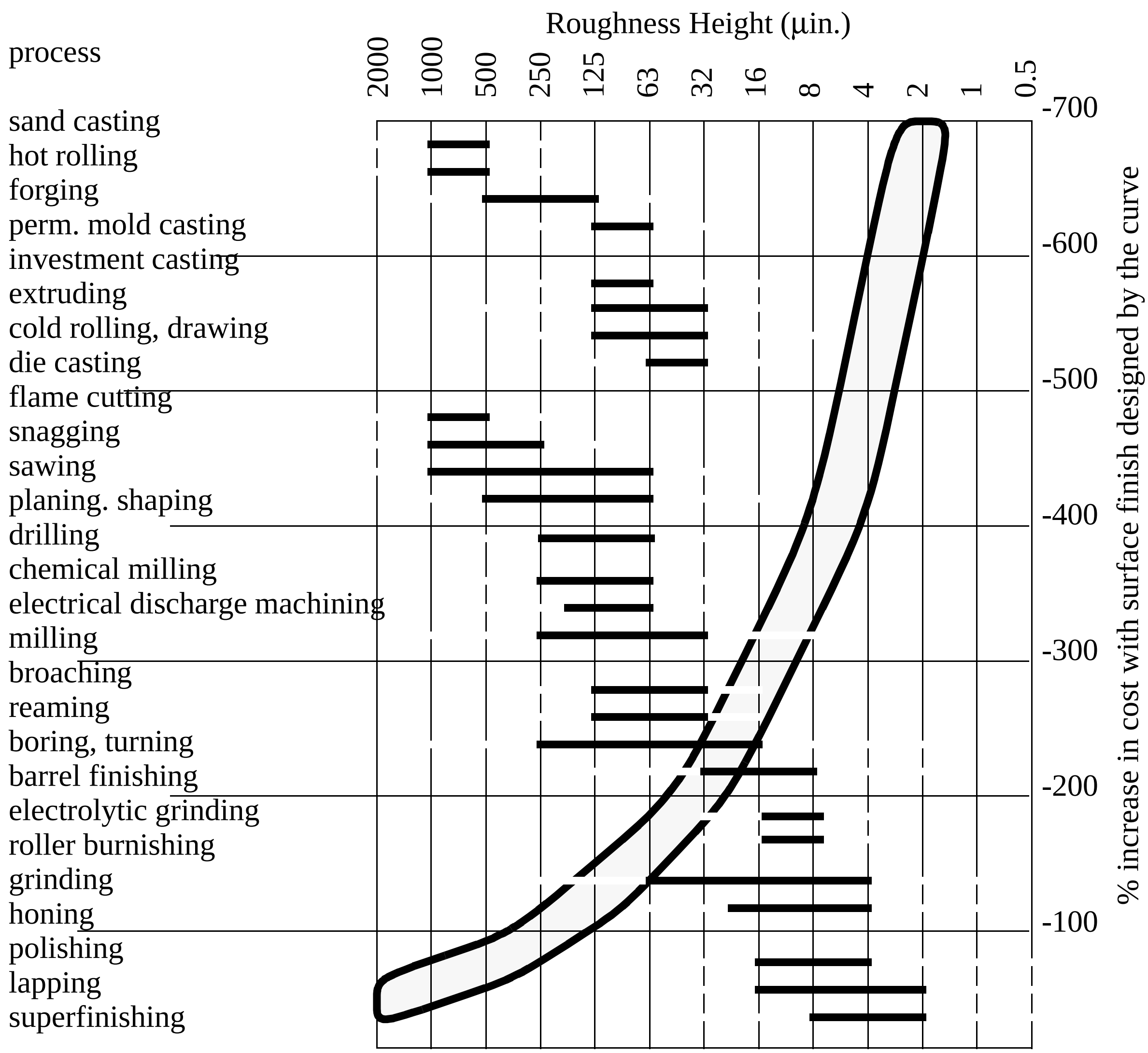


The two parallel lines L_1 and L_2 are positioned such that they cut off the peaks and valleys, given the mathematical constraints,

$$\sum P = 0.05l \qquad \sum V = 0.10l$$

h is the measure of peak to valley height

• A simple table that basically outlines the process capabilities of a number of processes is, [ANSI B46.1-1962]



Average usage of operation

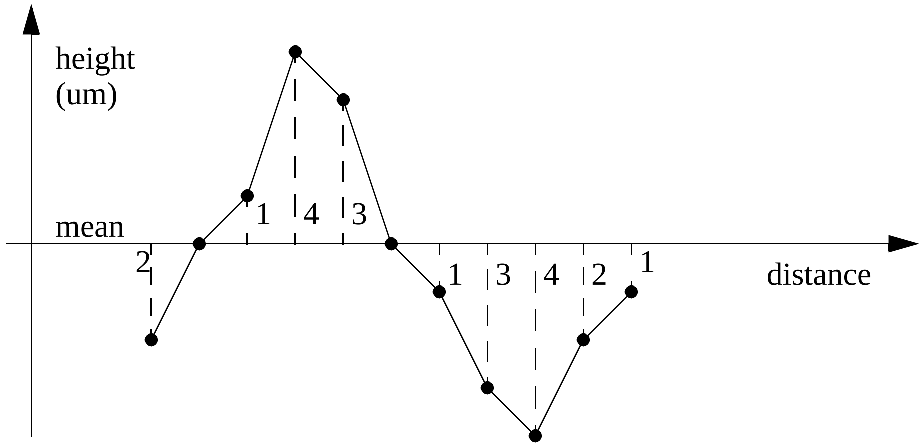
less common usage

• A table of roughness measurements is given below [Krar],

Tool	Operation	Material	speed	feed	tool	cutoff	Range	surface RMS
cutoff saw	sawing	2.5” dia. Al	320’/min		10 pitch saw	0.030”	1000	300-400
shaper	shaping flat surf.	machine steel	100’/min	0.005”	3/64” rad. HSS	0.030”	300	225-250
vertical mill	fly cutting	machine steel	820 rpm	0.015”	1/16” rad. stellite	0.030”	300	125-150
horizontal mill	slab milling	cast Al	225 rpm	2.5 “/min	4” dia HSS slab cutter	0.030”	100	40-50
lathe	turning	2.5” dia. Al.	500 rpm	0.010”	R3/64” HSS	0.030”	300	100-200
	turning	2.5” dia. Al.	500 rpm	0.007”	R5/64” HSS	0.030”	100	50-60
	facing	2” dia. Al.	600 rpm	0.010”	R1/32” HSS	0.030”	300	200-225
	facing	2” dia. Al.	800 rpm	0.005”	R1/32” HSS	0.030”	100	30-40
	filing	0.75” dia. steel	1200 rpm		10” lathe file	0.010”	100	50-60
	polishing	0.75” dia. steel	1200 rpm		#120 cloth	0.010”	30	13-15
	reaming	Al.	500 rpm		3/4” dia HSS	0.030”	100	25-32
surface grinder	flat grinding	machine steel		0.030”	60 grit	0.003”	10	7-9
cutter/tool grinder	cyl. grinding	1” machine steel		manual	46 grit	0.010”	30	12-15
lapping	flat lapping	.87”x5.” tool steel		manual	600 grit	0.010”	10	1-2
	cyl. lapping	0.5” dia. tool steel		manual	600 grit	0.010”	10	1-2

11.4 PRACTICE PROBLEMS

1. Calculate the CLA/Ra value for the wave form below.



ans. $$CLA = R_a = \frac{2+1+1+4+3+0+1+3+4+2+1}{11} = 2$$

2. What is the difference between surface texture and integrity?
ans. Surface integrity refers to all of the properties of the surface of a material, while surface texture on refers to the geometry of the surface.

3. Describe roughness, waviness and lay.
ans. Roughness is semi or completely random variation in the surface height, these are typically smaller in size. Waviness is a period or larger variation in surface height. This can be caused by warping or buckling, ripples, etc. Lay refers to a direction of a roughness pattern. For example when cutting with a lath the roughness will be different in the axial and radial directions.

4. What methods are used for measuring surface roughness?
ans. Surface roughness is normally measured with an instrument that drags a stylus across the surface (called a profilometer). The movement up and down is measured and used to calculate a roughness value.

5. Describe cutoff.
ans. Cutoff is the length of the surface that the stylus of the profilometer is allowed to move over.

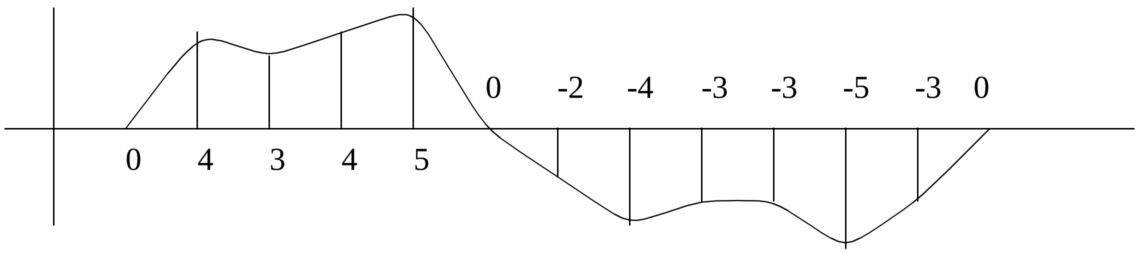
6. Two different surfaces may have the same roughness value. Why?
ans. A surface roughness value gives an indication of the rms value, but this can come in many forms. A regular looking roughness pattern may have the same roughness value as a shallower wave form with an occasional deep pit.

7. What will be the effect of a difference between the stylus path and the surface roughness?
ans. If the stylus path does not align with the lay of the roughness, then the roughness reading will be lower (or higher) than expected.

8. When is waviness a desirable and undesirable design feature?

ans. Waviness of a surface can be desirable when the surface is to have a rough appearance. If there is a moving mechanical contact between two surfaces waviness can lead to premature wearing of the parts.

9. Given the figure below indicating stylus height values for a surface roughness measurement, find the Ra and Rq value.



ans.

a	4
b	3
c	4
d	5
e	0
f	-2
g	-4
h	-3
i	-3
j	-5
k	-3
l	0

$$R_a = \frac{4+3+4+5+0-2-4-3-3-5-3-0}{10} = -0.4$$

$$R_q = \sqrt{\frac{4^2+3^2+4^2+5^2+0+2^2+4^2+3^2+3^2+5^2+3^2+0}{10}} = 3.71$$

10. How are surface roughness and tolerance of the process related?

ans. Surface roughness is a good indication of the ability of a process to control final dimensions. Therefore if the process cannot control the surface roughness, it will be unlikely that the dimensions can also be controlled.

11. How are tolerances related to the size of a feature?

ans. The tolerance/surface roughness graph is based on an important concept in manufacturing. There is a relationship between the scale of a dimension and the scale of a tolerance. In other words, if we make two parts in the same machine, but one is twice the size of the other, then its tolerance must be twice the size. Here we can see the more precise processes are near the bottom with a ratio of tolerance to dimension of 1/10000, the highest is about 1/10. Note: polishing and lapping are used to finish the production of gage blocks.

11.4.0.1 - Roundness Testing

• Roundness is of particular importance when designing components for fit and function.

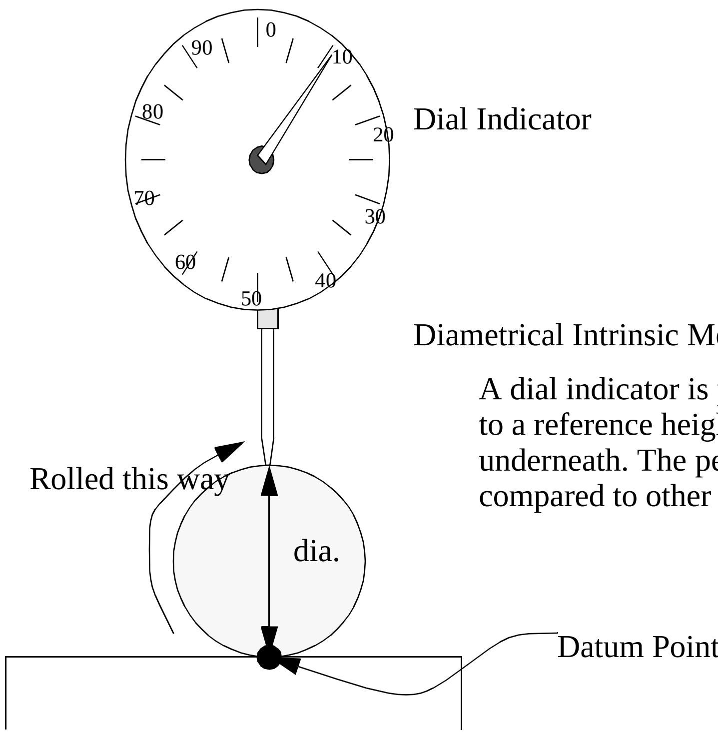
• Most of the methods considered so far are suited to measuring with single points, but a round shape is a collection of points, with each point having significant influence if out of tolerance.

• Precise roundness measurement equipment is expensive

• Two fundamental methods for measuring roundness are,
  - Intrinsic - uses points on the round surface to measure from
  - Extrinsic - uses a separate round surface for a reference (e.g. a precision bearing)

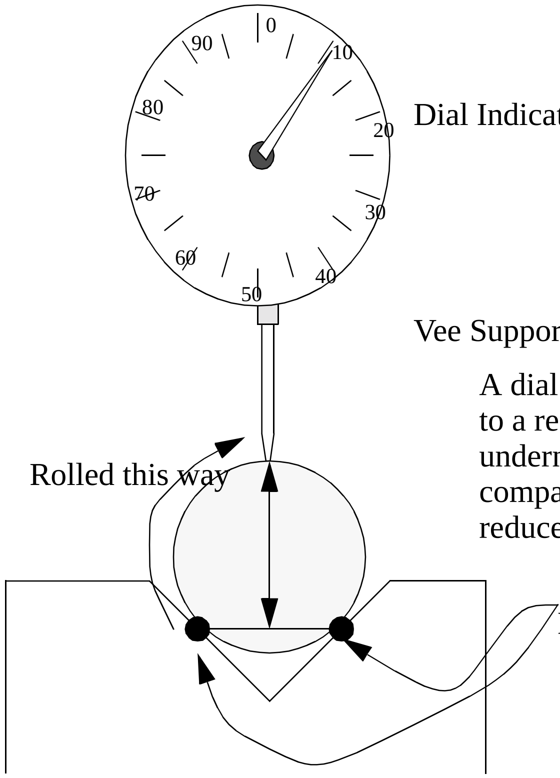
11.4.0.1.1 - Intrinsic Roundness Testing

• Three methods for Intrinsic roundness testing are shown below,



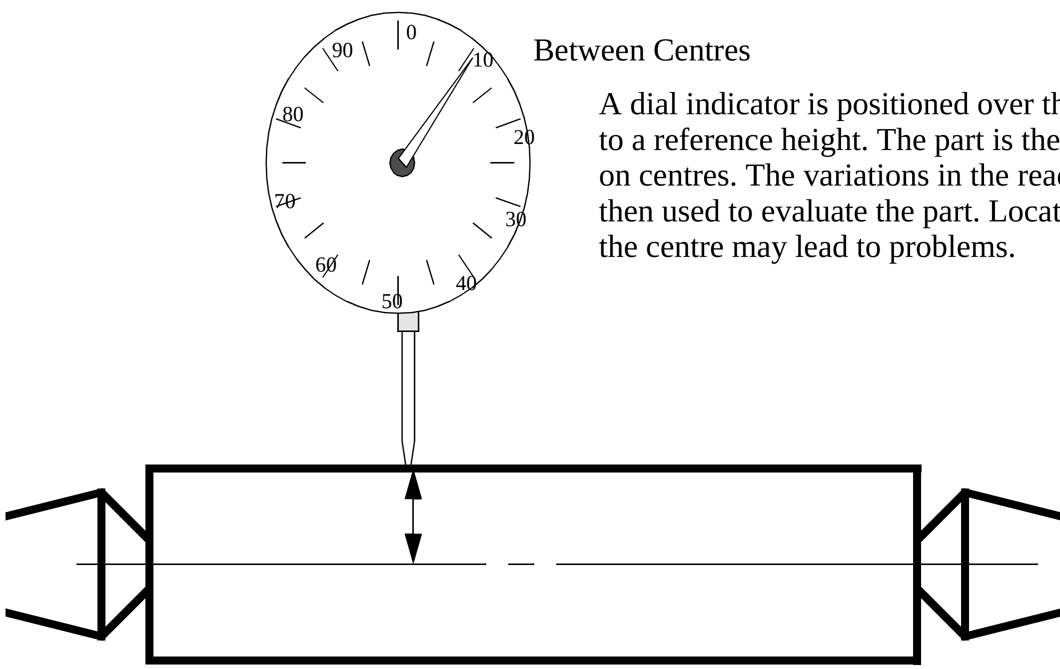
Diametrical Intrinsic Method

A dial indicator is positioned over the surface to a reference height. The part is then rolled underneath. The peak height can then be compared to other readings.



Vee Support Intrinsic Method

A dial indicator is positioned over the surface to a reference height. The part is then rolled underneath. The peak height can then be compared to other readings. The Vee support reduces the effect of a single datum point.



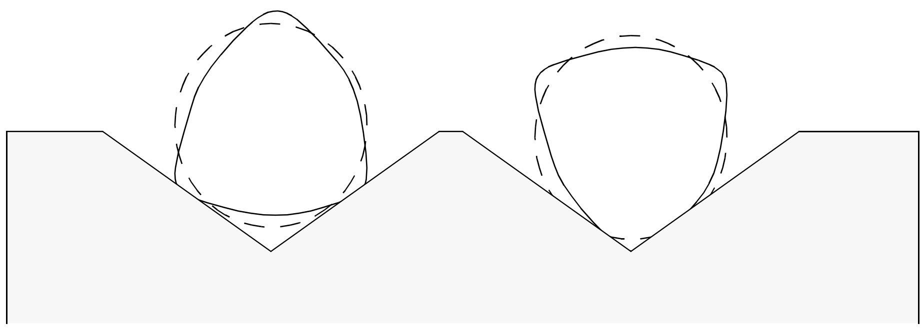
Between Centres

A dial indicator is positioned over the surface to a reference height. The part is then rotated on centres. The variations in the readings are then used to evaluate the part. Location of the centre may lead to problems.

• All three of the intrinsic methods are inexpensive

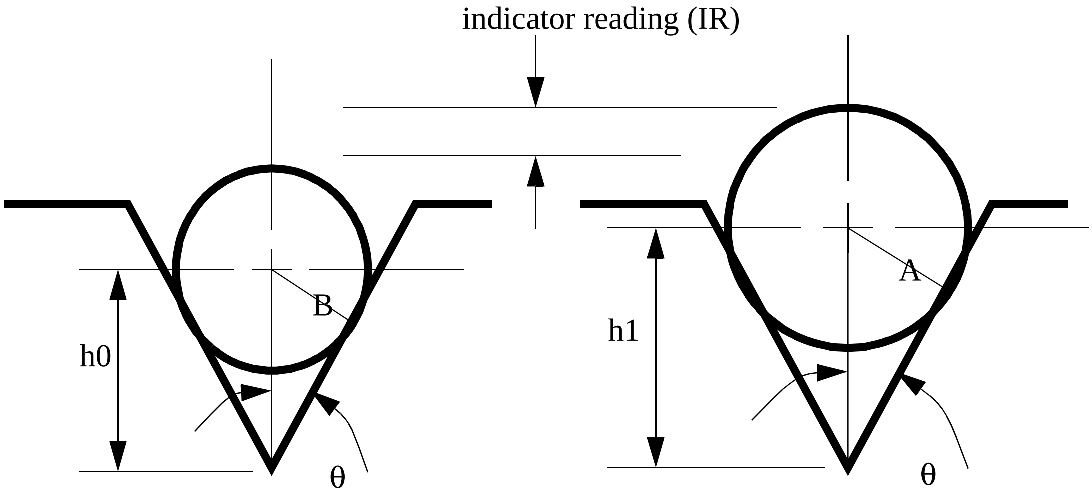
• The Intrinsic methods all have an important limitation. In particular, if the deformation of the round is small, the methods will deal with it reasonably, but if the deformation is large enough to make the shape non-cylindrical, then the results will err significantly.

With this test the two readings shown would indicate roundness, when in fact this is not true



This test would exaggerate the roundness error such that it would be greater than the actual error

• When using The Flat Plane, or the Centre to intrinsically measure roundness, the diameters can be directly obtained, but when using the Vee block, some additional calculations are required.



$$IR = \text{change in centre height + change in radii}$$

$$\therefore \quad = (h_1 - h_0) + (A - B) = \frac{A}{\sin\theta} - \frac{B}{\sin\theta} + (A - B)$$

$$\therefore \quad = A - B(\csc\theta) + (A - B)$$

$$\therefore IR = A - B(1 + \csc\theta)$$

where,

θ = 1/2 vee block angle

• The vee block method has particular disadvantages,
- a number of angles are required (the standard angle is 90°)
- only suitable for regular odd lobed figures

• The centre support method also has disadvantages,
- The part may be bowed, or warped
- off centre or degraded centre holes will decrease reading quality
- the centres themselves can also affect readings

11.4.0.1.2 - Extrinsic Roundness Testing

• The features of this methods are,
1. the reference datum is not points on the object, but a separate precision bearing
2. The axis of the part being measured is aligned with the machine bearing axis

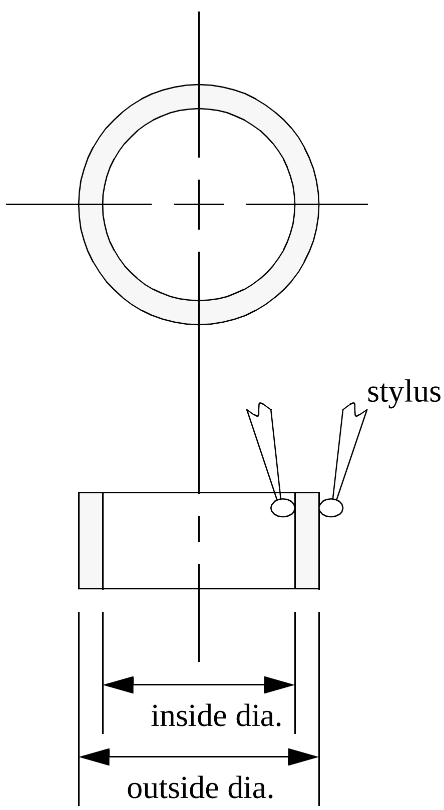
3. A stylus is moved in to contact the part, and then it moves about in a circular path
4. The deflection of the stylus is amplified onto a polar plot to be used in evaluation of the part

- We can measure the out of roundness value as the minimum distance between two concentric circles that enclose/envelope the trace profile. This distance must obviously be divided by the magnification.

- Only roundness deviations are amplified. This creates distortions in the trace.

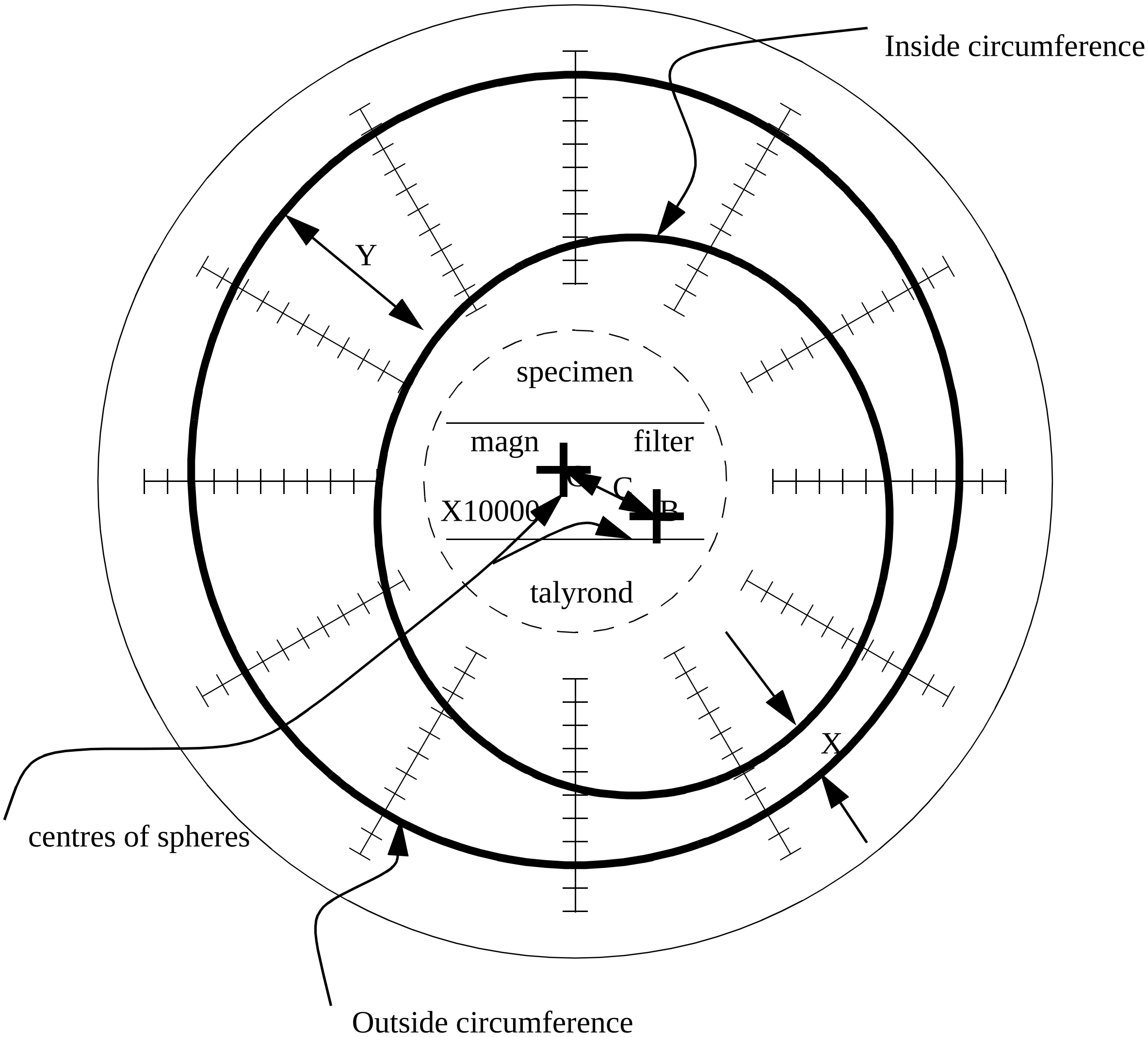
- The Talyrond machine also uses a low pass electronic filter to reduce the roughness that is shown on the plot. But this still shows the lobing.

- Eccentricity - the talyrond can also be used to detect concentricity. A simple example is a bearing race shown below.



the stylus measures the profile for both the inside and outside, and then these can be compared to determine concentricityXXXXXXX

- An example of the part discussed above, is now shown in a trace from the Talyrond



$$\text{ECCENTRICITY} = \frac{Y - X}{2} \times \frac{1}{magn} = \frac{C}{magn}$$

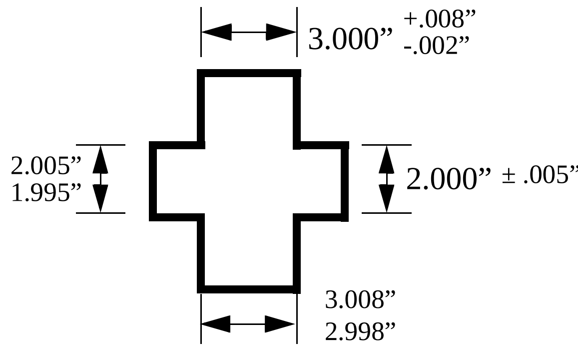
11.4.0.1.3 - Practice Problems

1. Show that the vee block method exaggerates errors using a round that is deformed into a triangular shape.

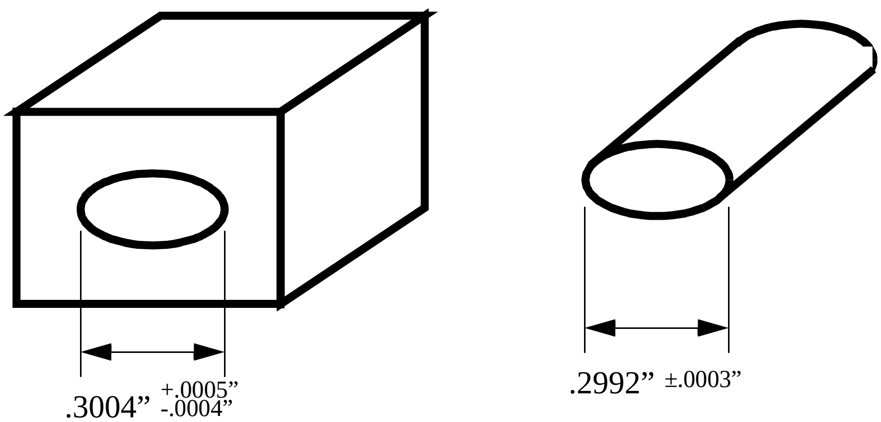
11.5 PRACTICE PROBLEMS

1. Select gauge blocks from an 83 piece set to build up a dimension of 3.2265”

2. Use the Unilateral System for a GO/NO-GO gauge design if the calibrated temperature is 72°F and the actual room temperature is 92°F. The shape to be tested is shown below.



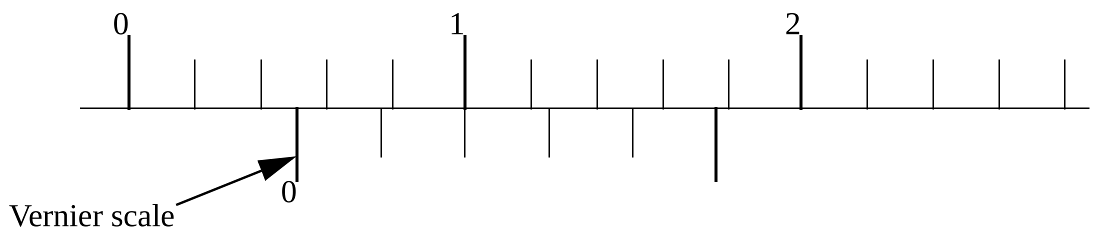
3. Find the Running Clearance fit category for the hole and shaft shown below.



4. Set up a sine bar (with 5 inches between cylinder centres) to provide an angle of 15°.

    a) What height of gauge blocks is required?
    b) Suggest an appropriate set of gauge blocks from an 81 piece set.
    c) What is the actual angle of the sine bar?
    d) If the room temperature is 95°F and the coefficient of expansion is .000001” per inch per °F, and the gauge blocks are calibrated to 68°F, what is the actual sine bar angle?
    e) Suggest a new gauge block stack for the conditions in d).

5. If the scale below reads .48, label the bottom vernier scale.



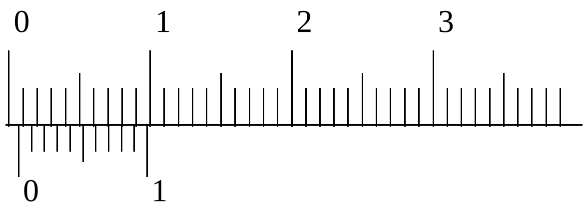
6. List four different reasons that a material like cheese would not be good for gauge blocks.

7. When using a dial indicator, is parallax or the principle of alignment more significant? Explain your answer.

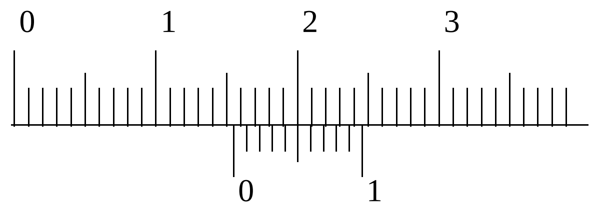
8. How can you verify that a standard square is 90°?

9. Design a GO/NO-GO gauge for a 5” by 7” square hole with tolerances of ±.1” on each dimension. Show the tolerances and dimensions for the gauges.

10. Write the values displayed on the vernier scales below.



Value: ______________________



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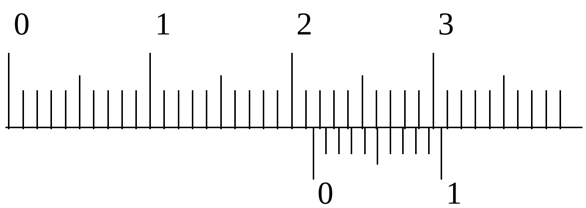

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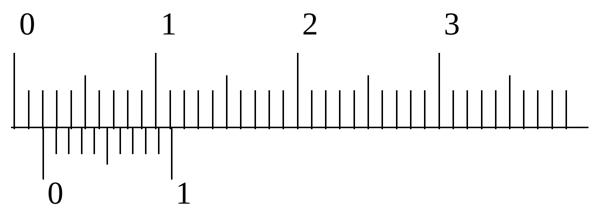


Value: ______________________

1. If the thimble on a micrometer is made larger, does it affect the ‘radial arm’, or the ‘inclined plane’ principle?

12. When a comparator approaches a workpiece from one direction, it will read a different value than when it approaches from the other way. Explain why.

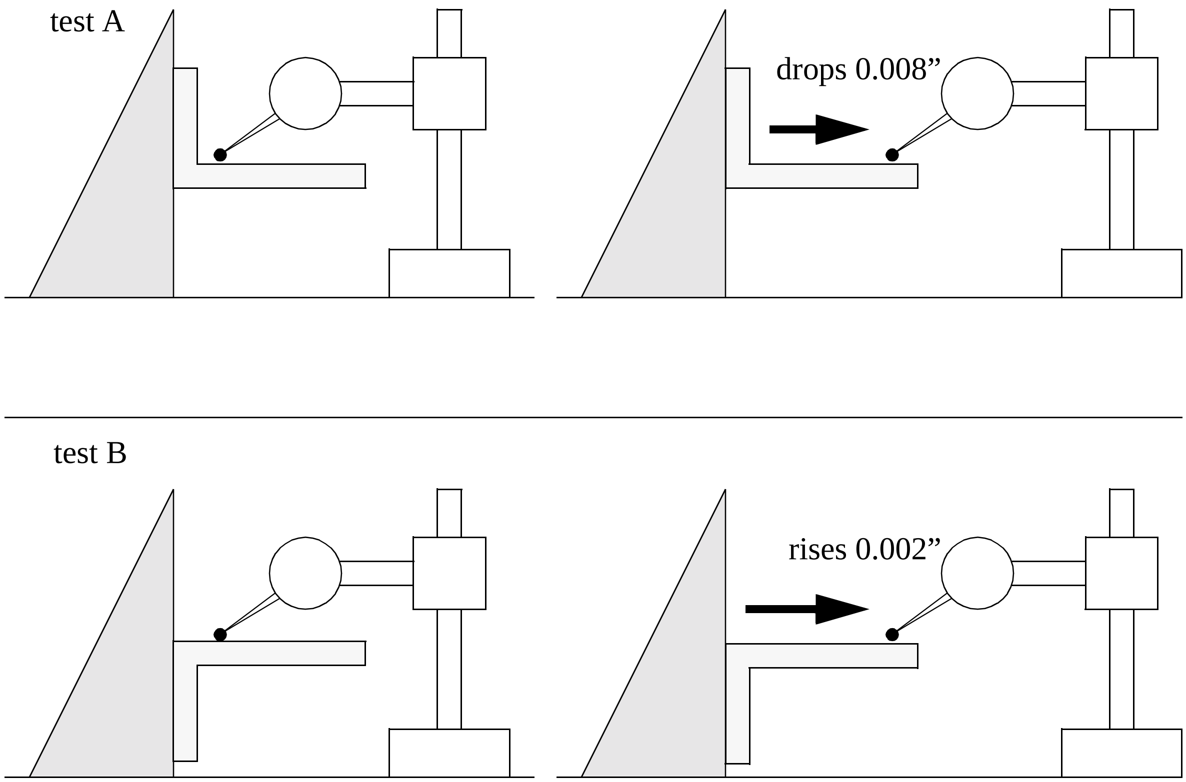
13. One type of fit is for Interchangeable Assemblies (it uses tolerances to ensure that parts can be made separately, but still fit together). What are the two other types of fits that were described in class? Describe why they are different.

14. A square hole has one dimension that will be checked with a GO-NOGO gauge set. The basic dimension is 2.005” ±0.003”. The gauge and hole are used in a room temperature of 105°F, but they should be accurate when at 60°F. The gauge coefficient of linear thermal expansion is 0.000001”, and the coefficient is 0.000002” for the material of the workpiece with the hole.

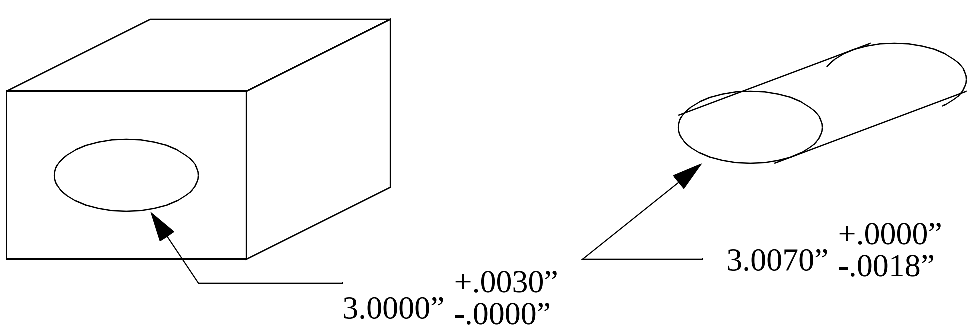
a) What sizes should the GO and NOGO gauges be?
b) Using the gauge block set shown below, list the gauge block stacks required.

15. A square is set up the two ways shown below, and a comparator is run from one end to the other. The resulting measurements result in the rises, or drops indicated. If the comparator is

run over a total distance of 5” for both measurements, what is the angle of the squares A and B?



16. The hole shaft pair is assembled with an LN fit.

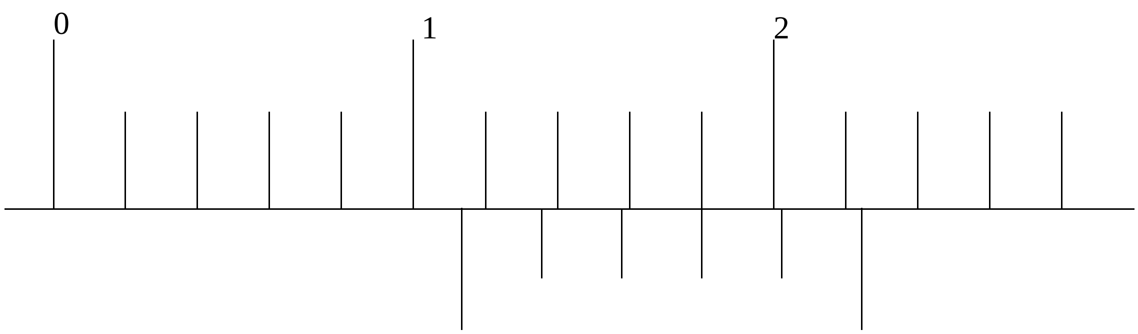


a) Draw the tolerance diagram.
b) Determine what the LN fit number is.

17. A sine bar will be used to give an angle of 82°35’

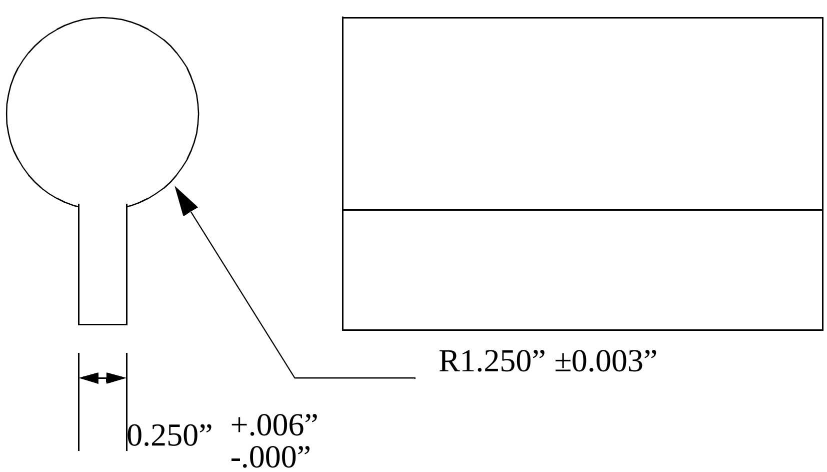
a) If the sine bar has 5” centres, what height will be needed?
b) Calculate the gauge block stack for the height in a).
c) What is the actual angle of the sine bar?
d) If the temperature in the room is 65°F at calibration, and 85°F at use, what change in angle does the sine bar have (coefficient of linear thermal expansion 0.000001 “/”°F for the sine bar, and 0.0000005 “/”°F for the gauge blocks)?
e) Could the sine bar be used with other instruments to improve accuracy?

18. Draw the number on the vernier scale below if the reading is 1.12



19. Parallax effects are more important than the principle of alignment for flow type pneumatic comparators - TRUE or FALSE

20. Draw GO/NO-GO gauges for the shaft below.



12. Select the most significant error that occurs when reading a scale that is properly used.
a) parallax errors where the scale is not parallel to the work.

b) change in the length of the scale due to a temperature change of 1°C.
c) reading with a scale that has a damaged end.
d) rounding off to the nearest division.

13. If we wanted to measure the diameter of the inside of a tip of a medical syringe (in the range of 0.005") what would be the best measuring instrument?
a) transfer gauge
b) tool makers microscope
c) GO/NOGO gauges
d) mechanical comparator

14. Which of the following statements is most correct?
a) vernier scales are used for linear measurements only.
b) micrometer scales are used for linear measurements only.
c) micrometer scales make vernier scales more accurate.
d) none of the above.

15. Which of the statements below is not correct?
a) the radial arm principle amplifies the rotation of a screw to a larger surface area and radial travel.
b) the inclined plane principle means that a small axial travel for a thread will be amplified to a much larger radial travel
c) the principle of alignment suggests that the dimension to be measured, and the measuring instrument should be aligned along the same axis.
d) all are correct.

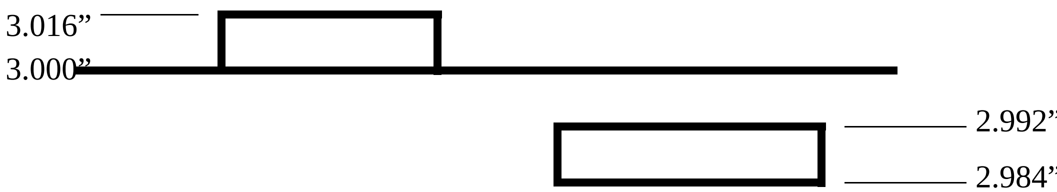
16. Which of the following physical principles is not used as a basis for comparators.
a) air pressure.
b) air flow.
c) the radial arm principle.
d) none of the above.

17. Surface plates are,
a) a surface that can be used to measure flatness without other equipment.
b) can be used for measuring small angles without other equipment.
c) a surface that can be used for measuring large angles without other equipment.
d) all of the above.

18. Sine bars,
a) are more accurate near 90°.
b) are more accurate near 0°.
c) are used with angular gauge blocks.
d) none of the above.

19. Given the diagram below, what will the average interference/clearance be?
a) 0.008"

b) 0.020”
c) 0.032”
d) none of the above



20. Given an 83 piece set of gauge blocks, how many different stacks 1.1117” in height can be built from the same set? (do not consider wear blocks)
    a) 1
    b) 2 or 3
    c) 4 or 5
    d) more than 5

21. Select the most appropriate statement.
    a) dial indicators use the inclined plane principle.
    b) dial indicators are a crude form of comparator.
    c) the range of the dial indicator is generally less than standard comparators.
    d) none of the above.

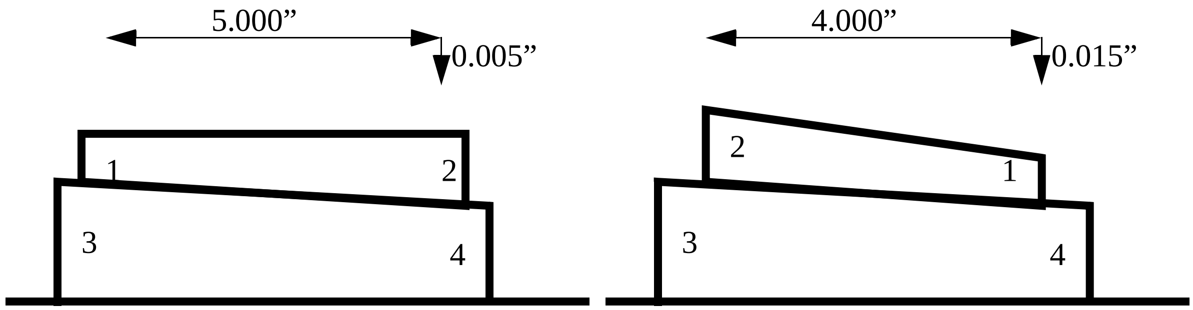
22. Briefly describe the relationship between tolerance and accuracy. (2%)

23. Find a gauge block stack that gives a value of 1.2351°. (3%)

24. a) given a metric gauge block set that is calibration grade (a tolerance of +0.00010mm to -0.00005mm) find the dimension and tolerance of a stack that is 3.2761cm in height. (4%)
    b) If the stack found in a) is increased in temperature from the ambient of 23°C to a higher temperature of 41°C, what is the new dimension and tolerance? (assume the coefficient of linear thermal expansion is $10^{-7}K^{-1}$. (8%)

25. Suggest a suitable comparator for measuring the diameter of a threaded nut. (3%)

26. Two blocks are stacked as shown below. In the first test we measure the drop in height (0.005”) from one side to the other (5.000”). Then the block on top is turned 180° (left to right)and the new drop in height (0.015”) is measured over a distance (4.000”). What are the angles of each of the blocks? (8%)

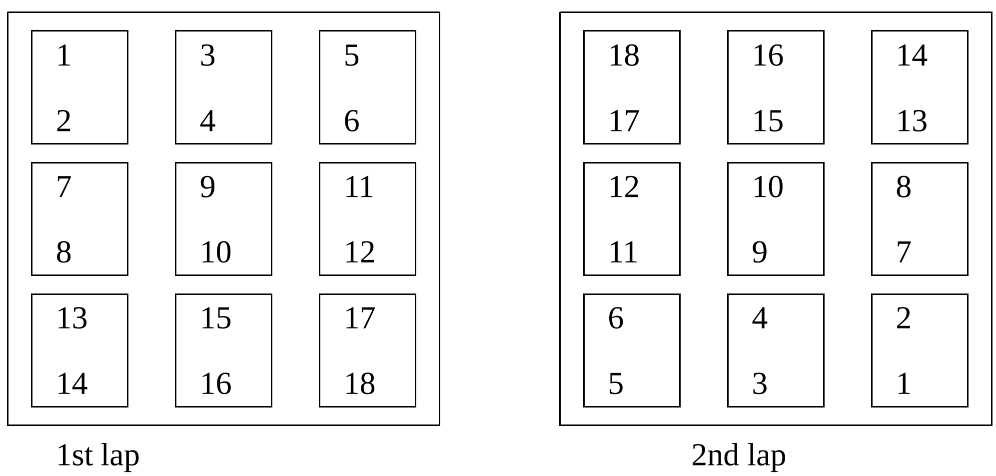


27. For mass production the inspector will need a fast and accurate instrument for measurement in order to ensure that part dimensions are between acceptable limits. What kind of category of instruments will you choose? Explain why. (3%)

28. What kind of magnification does the micrometer use? (2%)

29. Gauge blocks are made to such high precision they wring. What does the term wring mean? (2%)

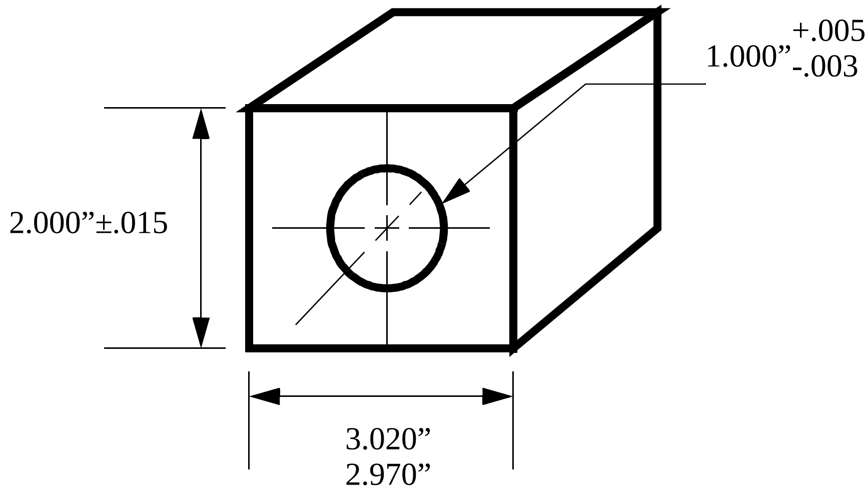
30. What would happen if the gauge blocks being lapped were first lapped in the pattern on the left, then second with the pattern on the right? (3%)



31. A steel scale with 1mm divisions will have a vernier scale added to get readings to 0.1mm. Use a diagram to show this scale and number the divisions. (6%)

32. List five potential applications of standards (5%)

33. Design Limit Gauges (GO/NOGO) for the block with a hole in it. Assume that the hole is always perfectly centered. (12%)



34. We are to measure a square hole that is to be measured at 25°C but when it is used at 40°C it is to be 2.000" exactly. Given that the coefficient of linear thermal expansion is $10^{-6}K^{-1}$ for the part and $10^{-7}K^{-1}$ for the gauge blocks (calibrated at 23°C) what height should the stack be? (5%)

35. METROLOGY

35.1 INTRODUCTION

35.1.1 The Role of Metrology

• modern manufacturing can produce features that are more accurate than we can measure by hand, therefore we need tools to assist us.

• These tools allow us to quantitatively evaluate physical properties of objects.

• EVERY industry uses these tools to some extent, for example,
- machine shops
- tailors
- dentists
- automotive manufacturers
- etc.

35.2 DEFINITIONS

Accuracy - The expected ability for a system to discriminate between two settings.

Assembly - the connection of two or more separate parts to make a new single part.

Basic Dimension - The target dimension for a part. This typically has an associated tolerance.

Dimension - A size of a feature, either measured, or specified.

Dimensional Metrology - The use of instruments to determine object sizes shapes, form, etc.

English System - See Imperial.

Error - a discrepency between expected, and actual values.

Imperial System - An older system of measurement, still in use in some places, but generally replaced by the metric system.

Limits - These typically define a dimensional range that a measurement can be expected to fall within.

Machine Tool - Generally use to refer to a machine that performs a manufacturing operation. This is sometimes confused with the actual cutting tools, such as a drill bit, that do the cutting.

Measurement - The determination of an unknown dimension. This requires that known standards be used directly, or indirectly for comparison.

Metric System - A measurement system that has been standardized globally, and is commonly used in all modern engineering projects.

Metrology - The science of measurement. The purpose of this discipline it to establish means of determining physical quantities, such as dimensions, temperature, force, etc.

Precision - Implies a high degree of accuracy.

Repeatability - Imperfections in mechanical systems can mean that during a Mechanical cycle, a process does not stop at the same location, or move through the same spot each time. The variation range is refered to as repeatability.

Standards - a known set of dimensions, or ideals to compare others against.

Standard Sizes - a component, or a dimension that is chosen from a table of standard sizes/forms.

Tolerance - The allowable variation in a basic dimension before a part is considered unacceptable

35.3 STANDARDS

- Standards are the basis for all modern accuracy. As new methods are found to make more accurate standards, the level of accuracy possible in copies of the standard increase, and so on.

- A well known metric standard is the metric 1m rod.

- Many standards are available for measuring, and many techniques are available for comparison.

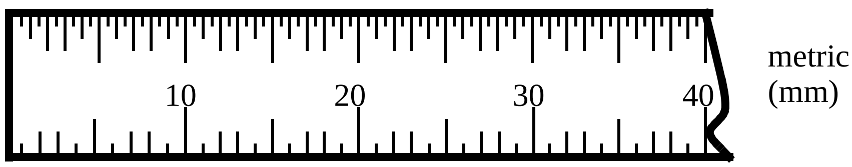
35.3.1 Scales

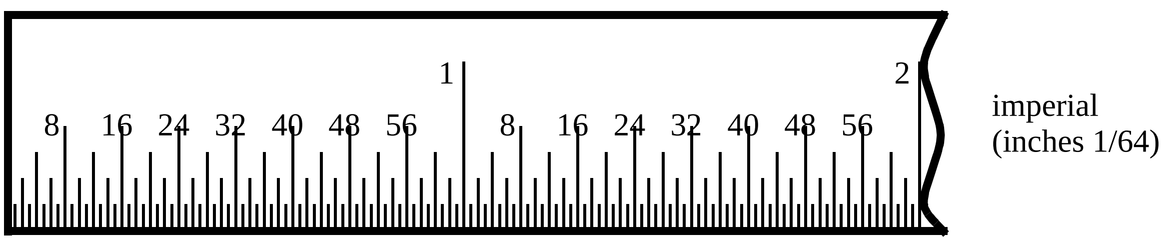
• The most common tool for crude measurements is the scale (also known as rules, or rulers)

• Although plastic, wood and other materials are used for common scales, precision scales use tempered steel alloys, with graduations scribed onto the surface.

• These are limited by the human eye. Basically they are used to compare two dimensions.

• The metric scales use decimal divisions, and the imperial scales use fractional divisions.

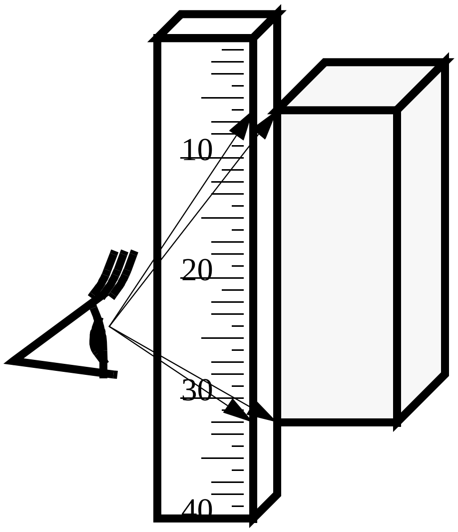




• Some scales only use the fine scale divisions at one end of the scale.

• It is advised that the end of the scale not be used for measurement. This is because as they become worn with use, the end of the scale will no longer be at a ‘zero’ position. Instead the internal divisions of the scale should be used.

• Parallax error can be a factor when making measurements with a scale.



If the instrument is not measured directly on, then there may be some error. Note: this would not occur if the scale was perfectly thin.

35.3.2 Calipers

• A tool used to transfer measurements from a part to a scale, or other instrument.

• calipers may be difficult to use, and they require that the operator follow a few basic rules,
  - do not force them, they will bend easily, and invalidate measurements made
  - try to get a feel, or personal technique for using these instruments.
  - if measurements are made using calipers for comparison, one operator should make all of the measurements (this keeps the feel factor a minimal error source).

• These instruments are very useful when dealing with hard to reach locations that normal measuring instruments cannot reach.

• Obviously the added step in the measurement will significantly decrease the accuracy

35.3.3 Transfer Gauges

• Small hole gauges can be inserted into a hole, as an adjustment knob is turned, the head expands to the size of the hole. The gauge can be removed and measured to determine the diameter of the hole. The end of this gauge appears as if a sphere with a shaft in it has been split into two halves.

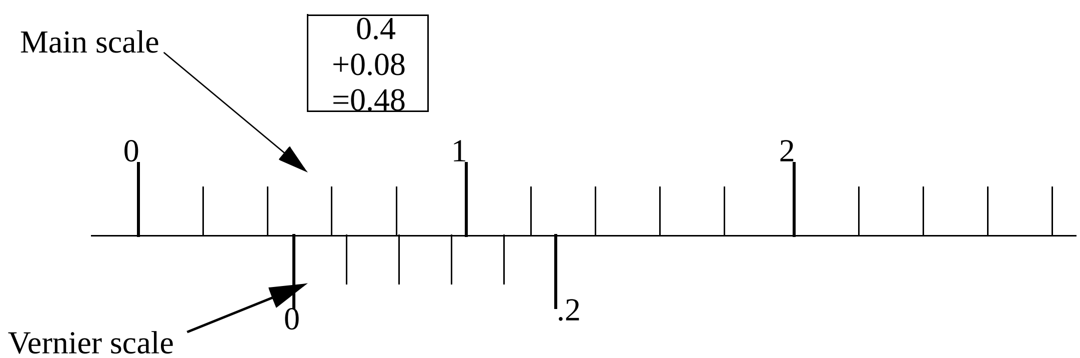
• Telescope gauges have two plungers that are springy, until locked in place. This can be put in holes or hard to reach locations, and used to transfer measurements to other measurement devices.

35.4 INSTRUMENTS

35.4.1 Vernier Scales

• Vernier scales have normal scale components, but also incorporate a small secondary scale that subdivides major increments.

• This secondary scale is based on a second scale that is one increment shorter than a main scale. If the secondary scale is compared to the main scale, it will indicate relative distance between two offsets.



• The scale pictured above would normally be on an instrument, and the main and vernier scales would slide relative to each other. The ‘0’ on the vernier scale would be used to take the reading from the main scale. In this example the main scale would read a value that is between 0.4 and 0.6. (Note: it is not considered good practice to round this to 0.5)

• The vernier scale can then be used to find the internal division, by looking for where the divisions in the top and bottom scales align. In this case the second internal division aligns with 1. Using the values on the vernier scale, we can see that the value for this division would be 0.08. The value from the vernier scale is added directly to the main scale value to get the more accurate results. 0.4+0.08 = 0.48.

• On imperial sliding vernier scales the main scale divisions are 0.050” apart, and on the vernier scale they are 0.049”, giving a reading of 0.001” per graduation.

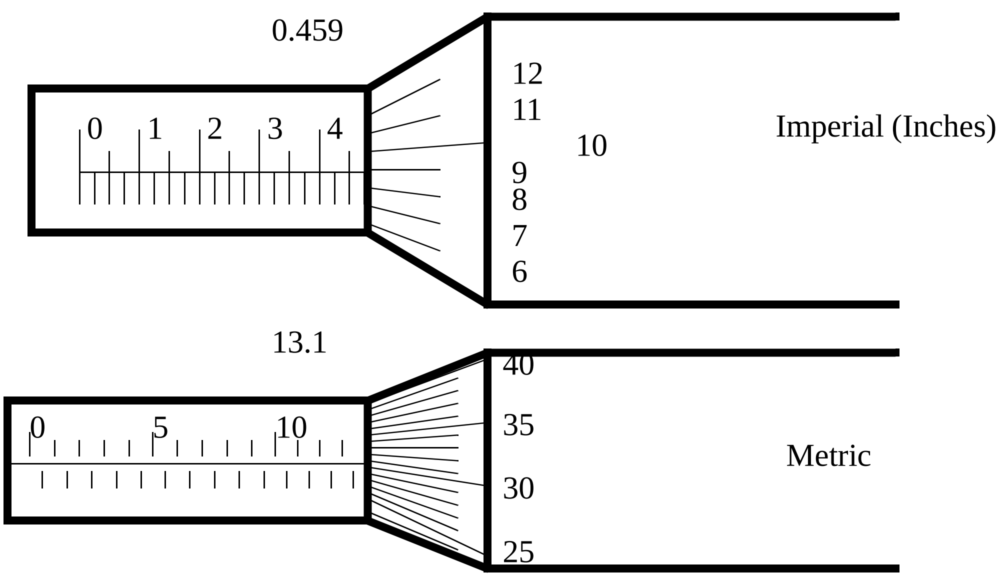
• On metric sliding vernier scales the main scale divisions are 1mm apart, and the vernier scale they are 0.98 mm, giving a reading of 0.02mm per graduation.

• Angular vernier scales are used on protractors, and are identical in use to linear vernier scales. The major protractor scales have divisions of 1 degree, and the vernier scale is divided into 5 minute intervals. One interesting note is that the vernier scale has two halves, one in the positive direction, and one in the negative direction. If reading from the left division, on the main scale, the right vernier scale should be used. And, when measuring from the right hand division on the major scale, the left vernier scale should be used.

35.4.2 Micrometer Scales

• This is a very common method for measuring instruments, and is based on the thread principle.

• In effect, as a thread is turned, a large motion on the outside of the thread will result in a very small advance in the position of the thread.



• The micrometers pictured above have major scales, as well as minor scales. The major scales are read first, and the micrometer scales are read second and the readings added on.

• The metric micrometer above reads 13.5 = 13.5mm on the major scale, and 31 = .31mm on the thimble, for a total of 13.81mm

• The Imperial scale above shows a micrometer reading of 4.5 = .45” on the main scale, and 9 = .009” on the thimble, for a total of .459

• On imperial micrometers the divisions are typically .025” on the sleeve, and 0.001” on the thimble. The thread used has 40 T.P.I. = a pitch of 0.025”

- Metric micrometers typically have 1 and 0.5 mm divisions on the sleeve, and 0.01mm divisions on the thimble. The thread has a pitch of 0.5mm.

- A vernier micrometer has the scales as pictured above, but also a vernier scale is included to provide another place of accuracy.

- Depth micrometers have an anvil that protrudes, out the end, and as a result the scales are reversed to measure extension, instead of retraction.

35.4.2.1 - The Principle of Magnification

- The operation of micrometers is based on magnification using threads.

- A large movement on the outside of the micrometer thimble will result in a small motion of the anvil.

- There are two factors in this magnification. First, the difference in radius between the thread, and the thimble will give a change in sensitivity relative to the difference in radii. Second, the pitch of the thread will provide a reduction in motion.

- The basic relationship can be seen below,

$$M = \frac{C}{D}\frac{\pi D}{pitch}$$

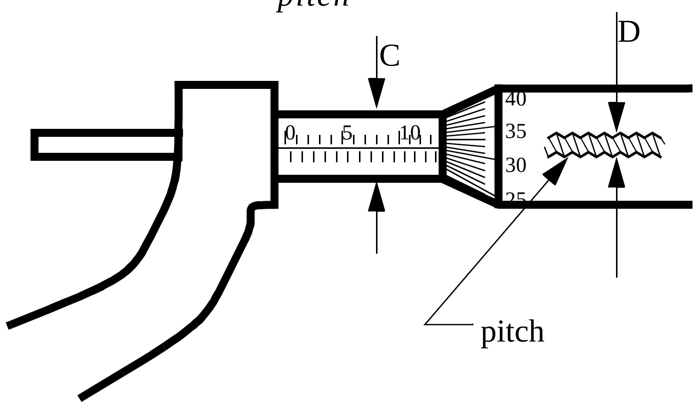
where,

M = magnification from the moving head to the hand motion
C = measuring diameter of the instrument
D = diameter of the thread
pitch = the number of threads per unit length

Radial Arm Principle of Magnification $= \frac{C}{D}$

Inclined Plane Principle of Magnification $= \frac{\pi D}{pitch}$

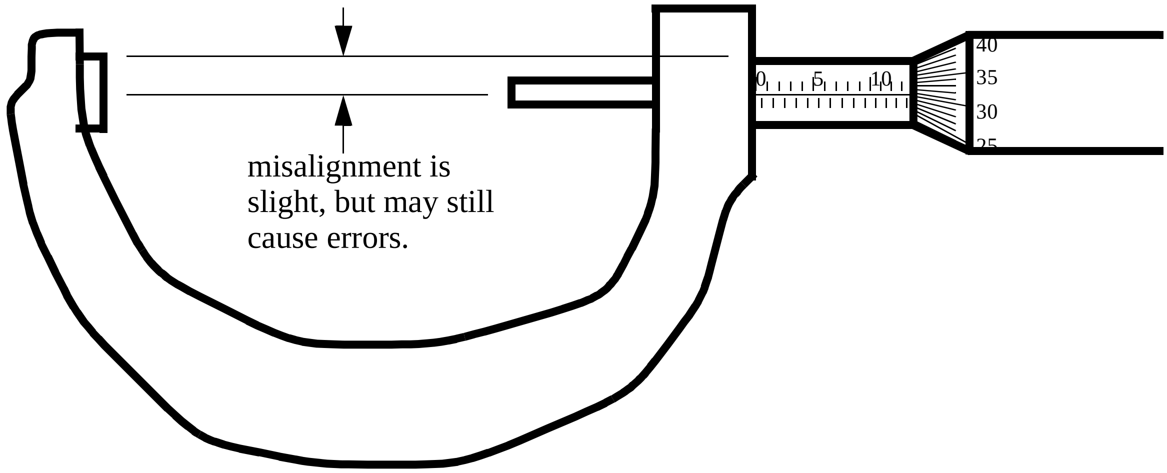
NOTE: magnification can result in greater sensitivity of an insrument to control, and reading by a user.



35.4.2.2 - The Principle of Alignment

• Basically, the line of the physical measurement should be such that it is coincident with the measurement axis of the instrument.

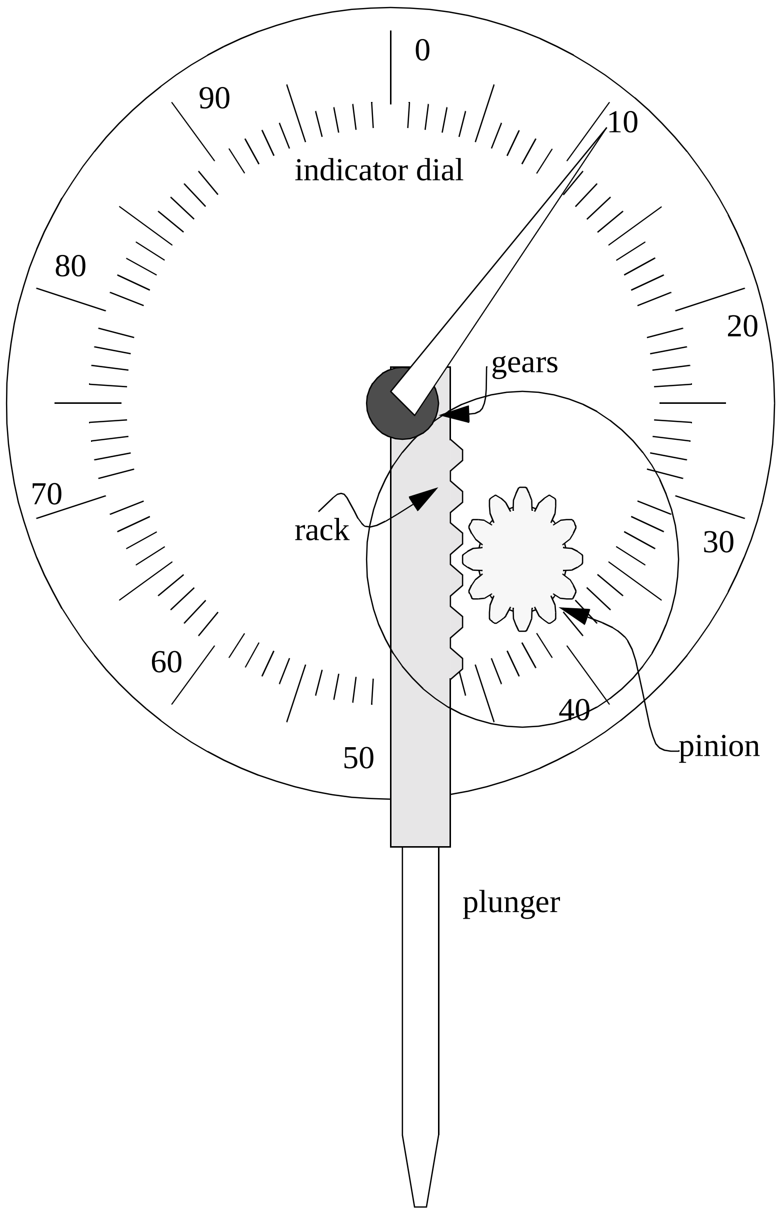
• If the measurement is out of line, it may lead to misreadings caused by deflections in the instrument.



• micrometers are generally better than sliding vernier calipers when considering this principle.

35.4.3 Dial Indicators

• Converts a linear displacement into a radial movement to measure over a small range of movement for the plunger.



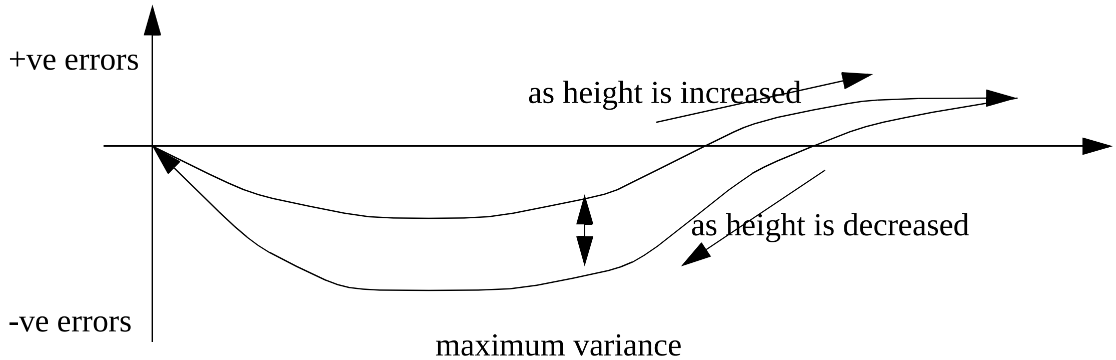
• The radial arm magnification principle is used here.

• these indicators are prone to errors caused by errors that are magnified through the gear train. Springs can be used to take up any play/backlash in the rack and pinion to reduce these errors.

• The gears are small, but friction can result in sticking, thus reducing accuracy

• A spring is used on the rack to return the plunger after depression.

• The problems mentioned earlier will result in errors in these instruments. If the dial indicator is used to approach a dimension from two different sides, it will experience a form of mechanical hysteresis that will bias the readings. An example of this effect is given below.



• In the graph shown, as the dial indicator is raised in height (taking care not to change direction), the errors are traced by the top curve. As the height of the dial indicator is decreased, the bottom curve is traced. This can be observed using gauge blocks as the known heights to compare the readings against.

• The causes of this hysteresis are bending strain, inertia, friction, and play in the instrument.

• Applications include,
  - centering workpices to machine tool spindles
  - offsetting lathe tail stocks
  - aligning a vise on a milling machine
  - checking dimensions

• These indicators can be somewhat crude for accurate measurements, comparators have a higher degree of sensitivity.

35.4.4 The Tool Makers Microscope

• Quite basically this is a microscope. But, it has lines added to the optics for visual reference, and micrometer dials, and angular verniers added to the stage to measure distances.

• Parts are put on the stage, and the microscope is focused. The stage can then be rotated, and translated precise distances to allow visually referenced measurements

• Such a microscope might have two micrometer heads for x-y translation of the stage. In addition, the stage can be rotated, and angular positions measures.

35.4.5 Metrology Summary

• We can discuss various instruments, and what they are used for.

Table 1: Fill in more later

Feature	SizeRange	Accuracy	Instrument	Comments
Angle	90°	yes/no	square	
	85°-95°	--	cylindrical square	
outside distance				
depth				

35.5 PRACTICE PROBLEMS

1. What are measurement standards?
ans. Standards are objects of known size, quantity, roughness, etc. These standards are used to calibrate and verify measuring instruments. As a result, measured values are more accurate.

2. What effect will temperature variation have on precision measurements?
ans. Temperature control during measurement is important because as materials are heated they expand. Each material expands at a different rate. This leads to distortion of parts and measuring devices that results in measurement errors.

3. How can a vernier scale provide higher accuracy?
ans. A vernier scale uses a second elongated scale to interpolate values on a major scale.

4. What are dimensional tolerances, and what are their primary uses?
ans. Dimensional tolerances specify the amount a dimension may vary about a target value. These are supplied by a designer to ensure the correct function of a device. If these tolerances are controlled the final product will work as planned.

5. Why is an allowance different from a tolerance?
ans. A tolerance is the amount a single dimension can vary. An allowance is an intentional difference between two dimensions to allow for press fits, running fits, etc.

6. What are fits?
ans. There are standard for different types of fits (e.g. press fit, running clearance). These specify the allowance of two parts, so that they may be made separately and then joined (mated) in an assembly.

7. What is the difference between precision and accuracy?
ans. Precision suggests a limit of technology, accuracy is the ability to achieve a value consistently. These are often interchanged because we are usually concerned with the accuracy when producing precision parts.

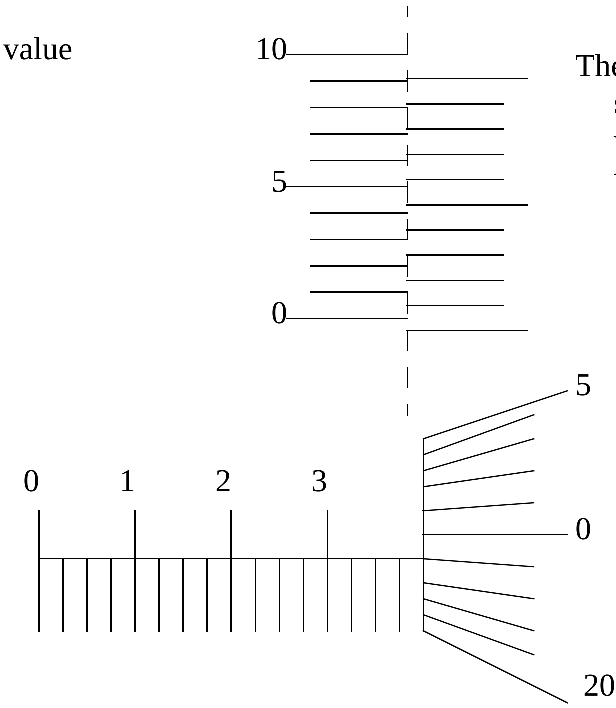
8. If a steel ruler expands 1% because of a temperature change, and we are measuring a 2" length, what will the measured dimension be?
ans. If we assume that only the steel rule expands, and not the steel part, we can calculate,

$$\frac{l_{bar}}{100+1} = \frac{l_{measures}}{100} \qquad l_{measures} = \frac{100(2)}{101} = 1.98\text{in}$$

9. Draw the scales for a vernier micrometer reading 0.3997".

ans.

For the 0.3997 value



The vernier scale to the left is shown as flattened out. It would typically be found on the back of the micrometer.

35.5.0.1 - Interferometry (REWORK)

- Light waves can be used to measure various attribute, such as distance by generating interference patterns.

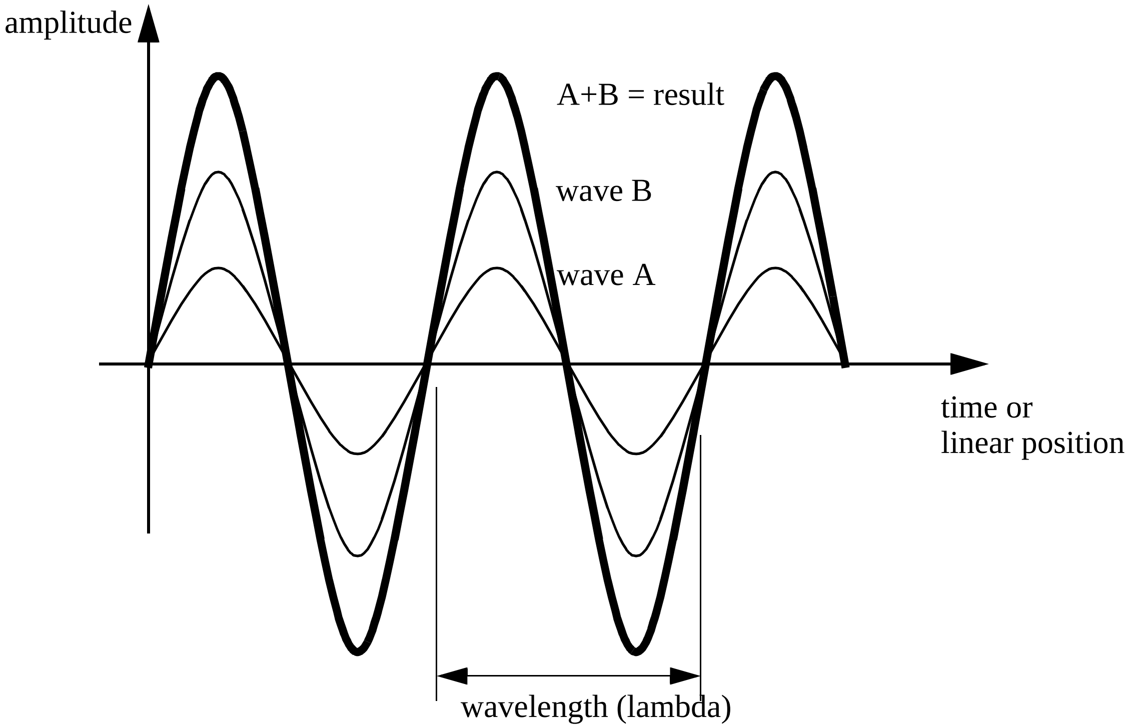
- In general, if we take a single beam of light, and split it, the two separated beams will have the same frequency, and phase. If the two beams take different length paths, but eventually intersect each other, then they will form interference patterns, much as is found in wave tanks.

35.5.0.1.1 - Light Waves and Interference

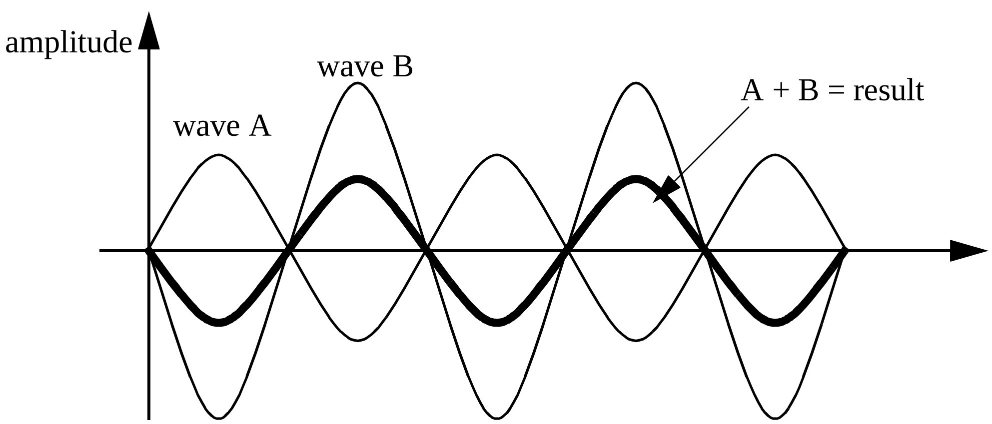
- In reality normal light from the sun, or a light bulb, etc. has many frequencies, directions, and phases. But when we use special light sources, such as lasers, the light is monochromatic. Each photon is in phase, and has the same frequency as all the others. In effect we have a ‘super-photon’.

- Aside: as a simple review, recall that light is just an electromagnetic field the is becoming more and less intense at a very high frequency. If you could shake a simple magnet fast enough (this is impossible physically) you could make light, radiowave, X-rays, heat that you can feel, etc.

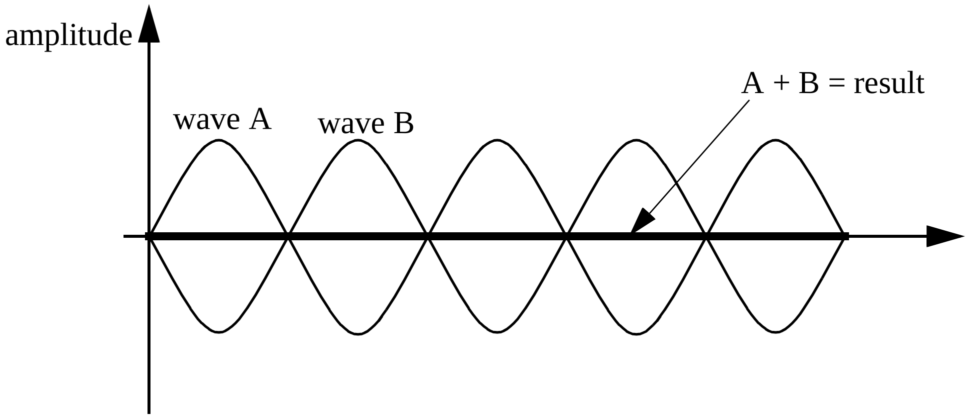
- another principle of importance to our discussion is superposition, and interference.If we have two or more photons in phase, their individual intensities will add together to a new higher intensity.



• The superposition approach where waves are added, also has the effect of reducing wave heights when waves are out of phase. At the most extreme, when the waves are 180° out of phase, the resultant wave is the difference in height.



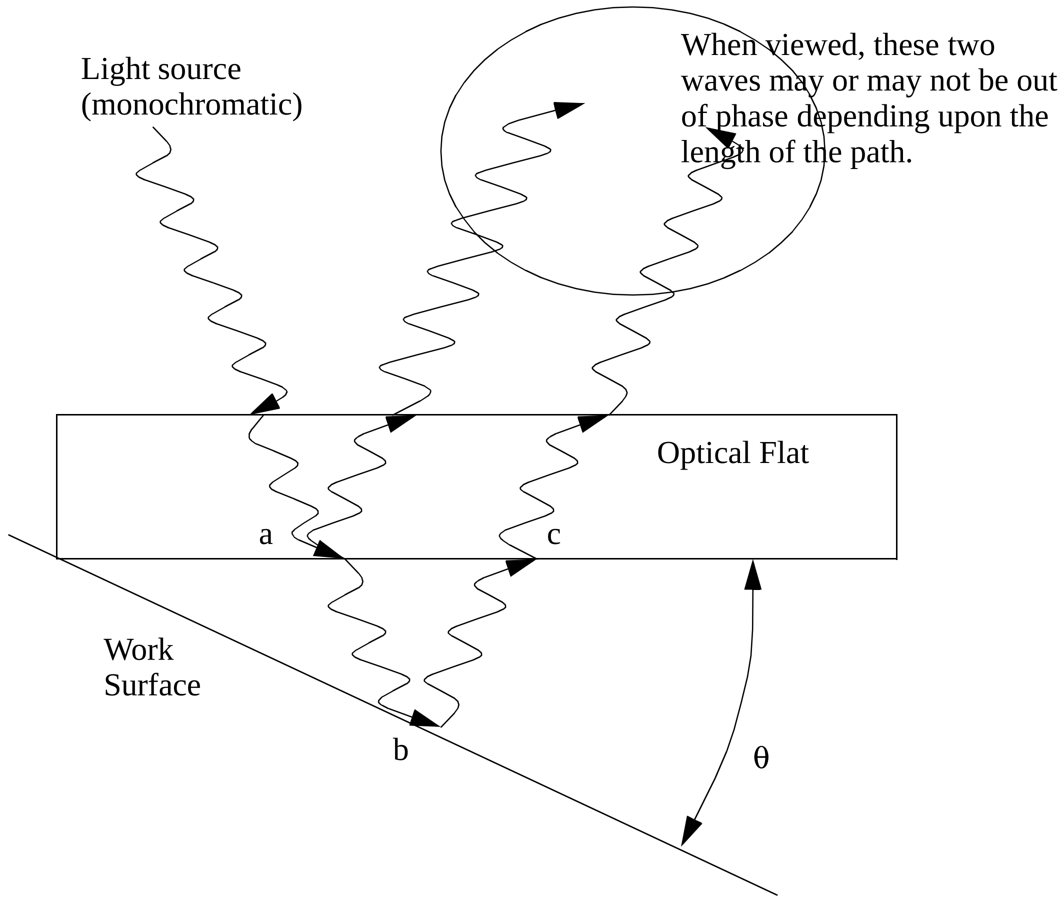
• If the two out of phase waves are the same magnitude, then they will cancel out (interfere) completely,



35.5.0.1.2 - Optical Flats

• Optical Flats use a transparent surface with high precision finishes.

• a monochromatic light is shone through the optical flat, at the bottom interface, some of the light is reflected back, while some light escapes to reflect off the surface, and back through the flat. It is when some of the light is reflected at the back side of the optical flat that the beam is split. The distance between the flat and the surface then changes the pathlength of the two beams. As they are reflected back, the light waves interfere, and create light/dark fringes that are a function of distance between the flat and the plat.



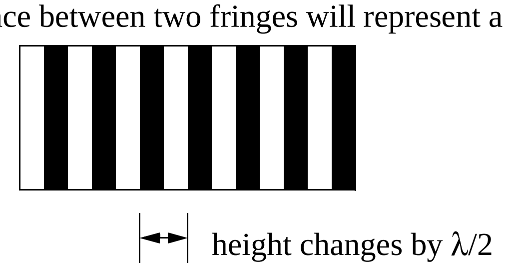
• There are some mathematical relationships that should be observed,

1. θ should be small. Large values will introduce problems, and decrease accuracy.
2. the distance ‘abc’ will determine if a light/dark stripe is seen.

$$ab + bc = \lambda\left(n + \frac{1}{2}\right) \qquad\qquad ab + bc = \lambda n$$

Dark   Light

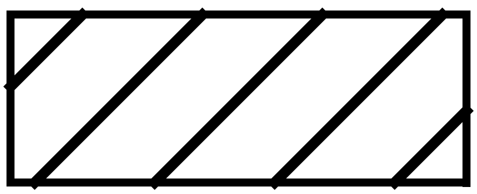
3. The distance between two fringes will represent a change in height of λ/2



35.5.0.1.3 - Interpreting Interference Patterns

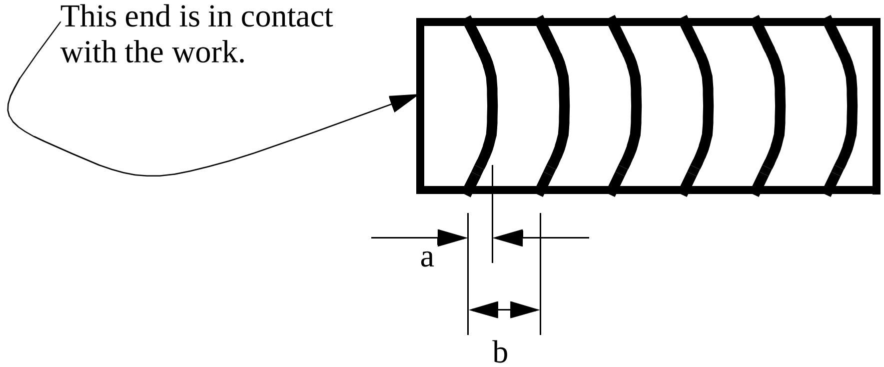
• Lets consider a lapped surface that is examined under an optical flat, with a helium light (with a wavelength of 23.2 μin.).

Case 1: Parallel equally spaced lines indicate that the surface is flat.

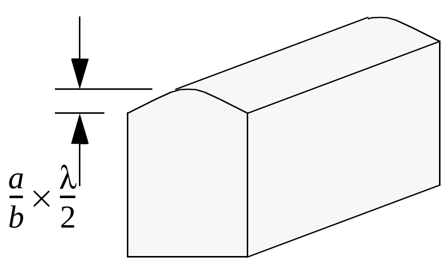


Question: why are the lines in a diagonal pattern instead of vertical?

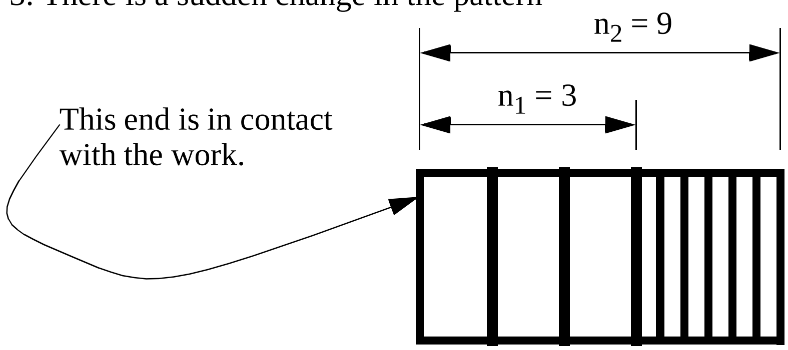
Case 2: Curves lines in a regular pattern



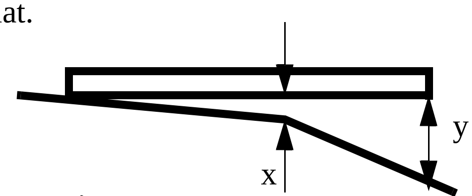
This surface curves up in the centre, but in a uniform way. Therefore the part might look something like the exaggerated view below,



Case 3: There is a sudden change in the pattern



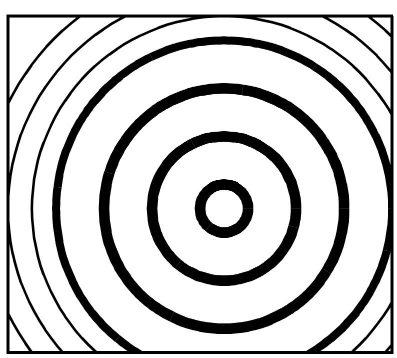
The slope of the surface changes part way along the optical flat. The fact that in both of the two regions the lines are parallel and uniform, means the work surface is flat.



$$x = n_1 \times \frac{\lambda}{2} =$$

$$y = n_2 \times \frac{\lambda}{2} =$$

Case 4: A radial circular pattern is observed

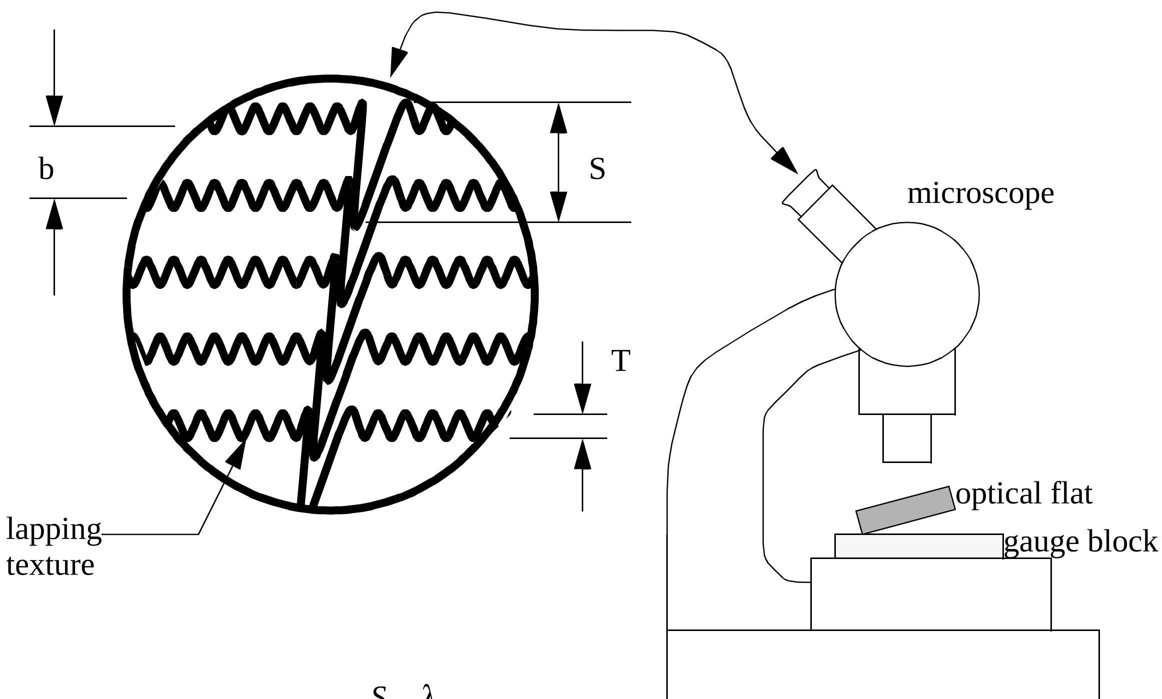


Practice: Draw the Section this would represent.

35.5.0.1.4 - Types of Interferometers

• There are three basic types of interferometers for surface texture measurement
- Interference microscopes
- flatness type interferometer
- gauge block interferometer

• Interference Microscopes - used for analysis of surface texture analysis. The example below shows the instrument being used to examine a gauge block.



$$\text{scratch depth} = \frac{S}{b} \times \frac{\lambda}{2}$$

$$\text{texture height} = \frac{T}{b} \times \frac{\lambda}{2}$$

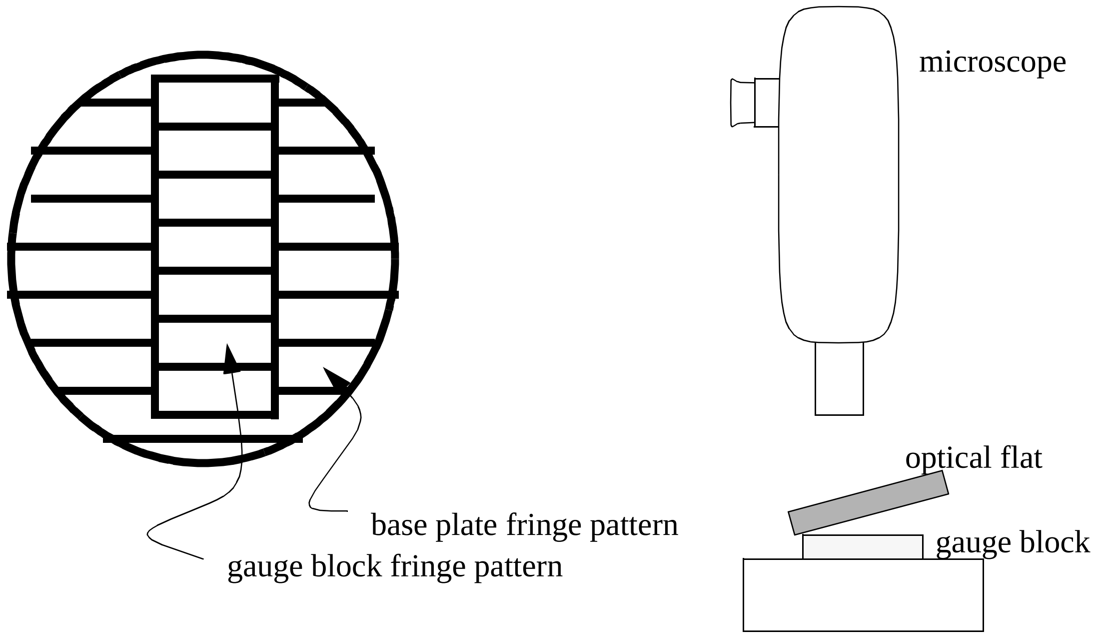
$$R_a(\text{estimated}) = \frac{T}{4b} \times \frac{\lambda}{2}$$

This assumes a triangular shape of the surface as discussed earlier.

Note:

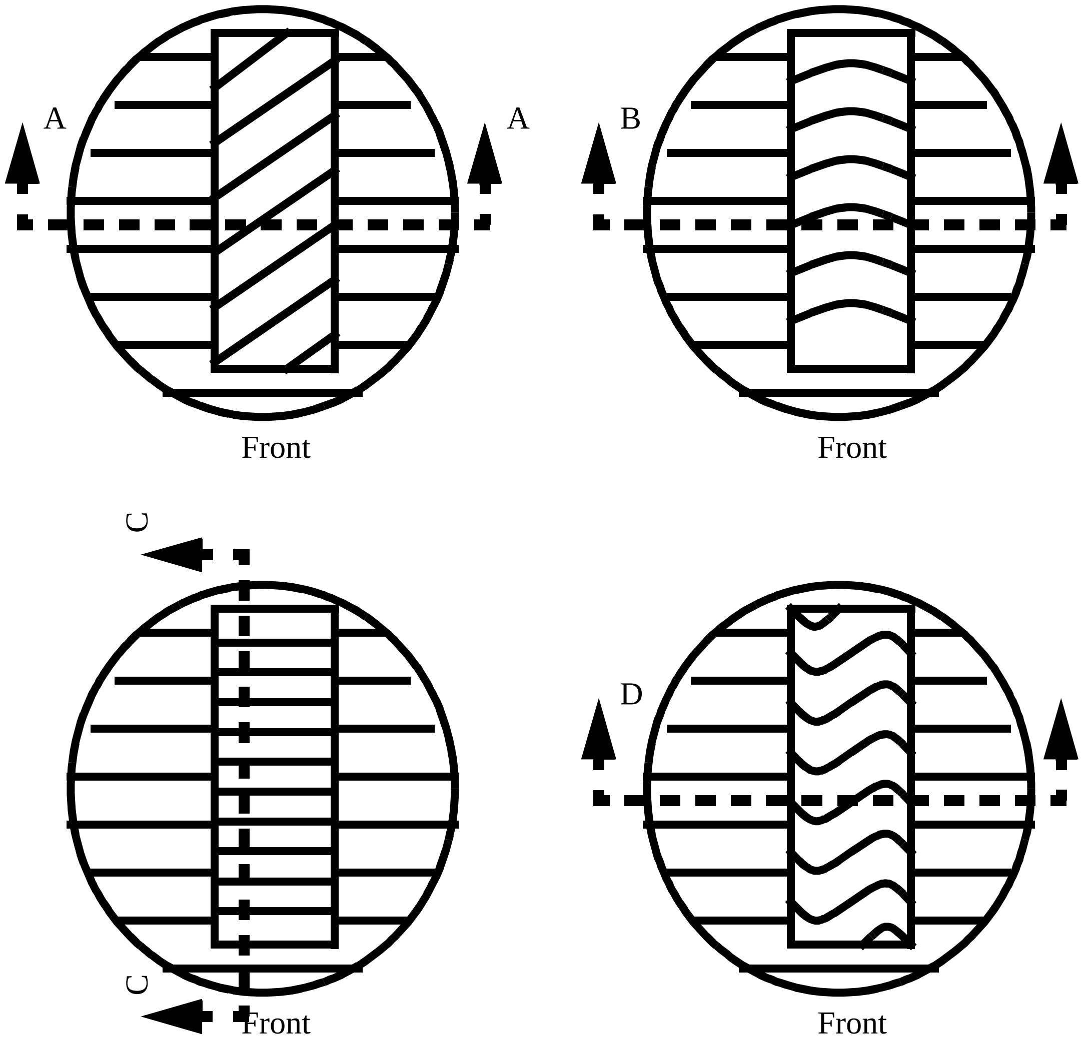
- The lay on gauge blocks is along the length
- The Mercury wavelength is approximately 20 μin.

• Flatness type interferometer - this type of interferometer is used to compare the parallelism of the top and bottom faces of the gauge blocks. This microscope has a base plate with a lapped finish. The gauge blocks are wrung to the surface, and then the patterns on the top and bottom are compared.

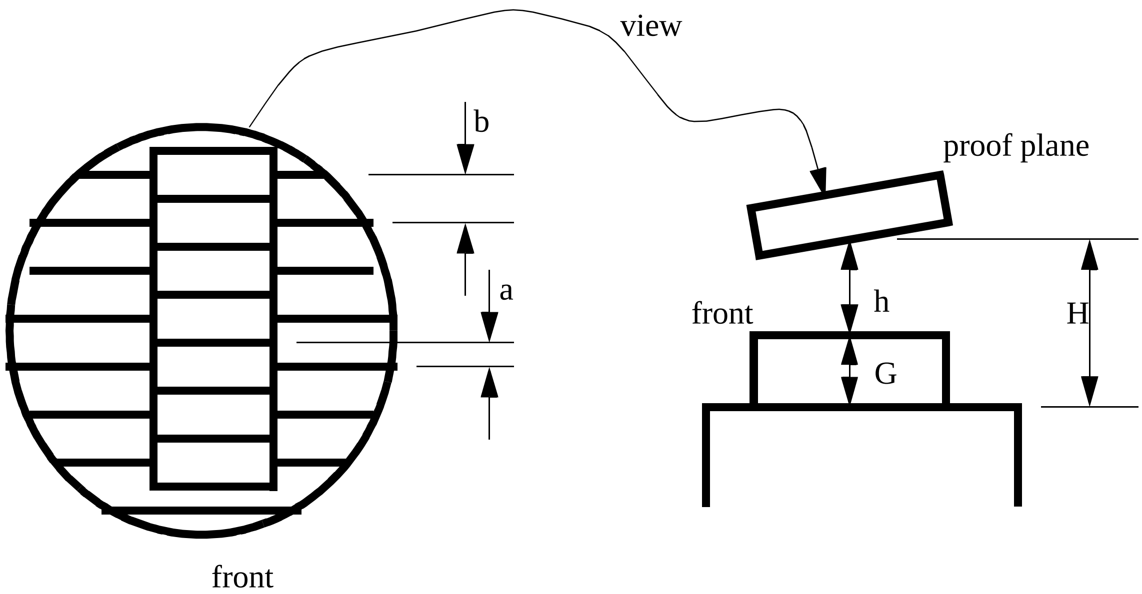


Because the fringe patterns for the gauge block, and the base plate have the same spacing, the two sides of the gauge block are parallel.

Practice Problem: Draw sections for the views below, and estimate errors in flatness and parallelism. (These have been taken on a flatness type interferometer, using 20 μin. wavelength light)



• Gauge Block Interferometer - This instrument is used for height measurements. using four different frequencies of light. (red, green, blue, violet). The example below shows and example of its use.



The gauge block is a 0.3” specimen, and it will be measured with the red, green, and violet light components.

$$G = H - h = n \times \frac{\lambda}{2} + \frac{a}{b} \times \frac{\lambda}{2} = \frac{\lambda}{2}\left(n + \frac{a}{b}\right)$$

where,

$$n = \text{whole number of } \frac{\lambda}{2} \text{ intervals, and } \frac{a}{b} = \text{the fraction of } \frac{\lambda}{2}$$

For each frequency of light used, there will be a different ‘n’ value. In addition, the a/b fractions will also differ.

$$f_1 = \frac{a_{red}}{b_{red}} \qquad f_2 = \frac{a_{green}}{b_{green}} \qquad f_3 = \frac{a_{violet}}{b_{violet}}$$

Next, we will relate the three readings,

$$G = \frac{\lambda_1}{2}(n_1 + f_1) = \frac{\lambda_2}{2}(n_2 + f_2) = \frac{\lambda_3}{2}(n_3 + f_3)$$

Next, use the ideal value of the gauge block, and then combine it in with the previous equations,

$$G_N = \frac{\lambda_1}{2}(N_1 + F_1) = \frac{\lambda_2}{2}(N_2 + F_2) = \frac{\lambda_3}{2}(N_3 + F_3)$$

where,

$$N_1 = int\left(\frac{G_N}{\left(\frac{\lambda_1}{2}\right)}\right) \qquad\qquad F_1 = \frac{G_N}{\left(\frac{\lambda_1}{2}\right)} - N_1$$

N_2, F_2, N_3, F_3 is similar to the above equations

Assuming $G > G_N$, we can combine the equations,

$$G - G_N = \frac{\lambda_1}{2}[(n_1 - N_1) + (f_1 - F_1)]$$

The equation above is similar for the other two colours

The calculations continue to find values for $(n_1 - N_1)$, $(n_2 - N_2)$, $(n_3 - N_3)$, these will be small whole numbers.

• To consider an example of measuring the height of a gauge block using the interferometer,

Given that a gauge block has a height of 0.3", and we want to find the height in more detail. We are using the gauge block interferometer, with red, green, and violet light.
The basic observations, and known values to start are,

red	$\lambda_1 = 25.348478\mu\text{in.}$	$f_1 = \frac{a}{b} = 0.35$
green	$\lambda_2 = 20.023055\mu\text{in.}$	$f_2 = \frac{a}{b} = 0.35$
violet	$\lambda_3 = 18.418037\mu\text{in.}$	$f_3 = \frac{a}{b} = 0.95$

The following equations must be solved,

$$G - G_N = \frac{\lambda_1}{2}[(n_1 - N_1) + (f_1 - F_1)]$$

$$G - G_N = \frac{\lambda_2}{2}[(n_2 - N_2) + (f_2 - F_2)]$$

$$G - G_N = \frac{\lambda_3}{2}[(n_3 - N_3) + (f_3 - F_3)]$$

The solution to these equations is not direct, but a table can help find the values,

colour	λ X10^{-6}"	f fraction a/b	N	F	f-F	coincide at	mean error in gauge block error
red	25.35	0.35	23670.06	0.06	0.29	2.29	
green	20.02	0.35	29965.46	0.46	0.89**	2.84	28.7 μin.
blue	18.42	0.95	32576.76	0.76	0.19	3.13	

** this value is arrived at by 1.35 - 0.46, not 0.35 - 0.46

These values are now substituted back in to give the equations,

$$G - G_N = \frac{25.35}{2}[(n_1 - N_1) + (0.29)]$$

$$G - G_N = \frac{20.02}{2}[(n_2 - N_2) + (0.89)]$$

$$G - G_N = \frac{18.42}{2}[(n_3 - N_3) + (0.19)]$$

XXXXXXXXXXXXXX
given that the values for (n_1-N_1), (n_2-N_2), (n_3-N_3) are small whole numbers, we can now find the values looking for the point of coincidence on the special slide rule. In this example we found,

$$(n_1 - N_1) = 2$$

$$(n_2 - N_2) = 2$$

$$(n_3 - N_3) = 3$$

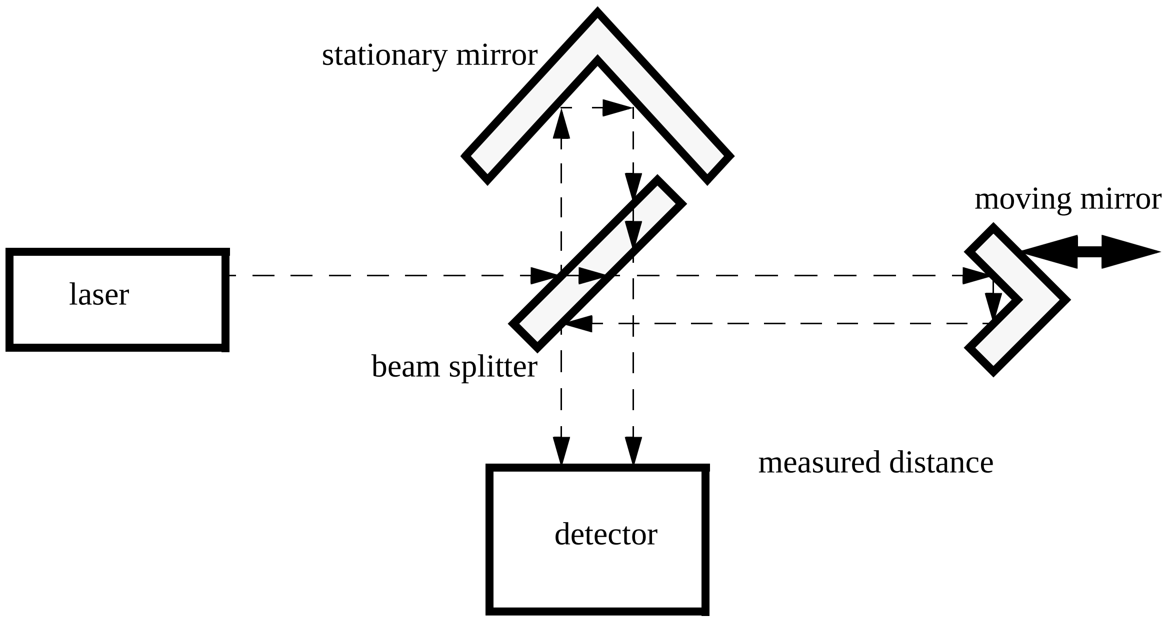
• The use of this magical slide rule is described below,

This seems to be a special ways to search for actual values when only the fractions are known. The basic procedure is, (assuming the numbers are .45 and .56)

1. pick one of the two values (say .45).
2. start looping from 0.45, 1.45, 2.45, 3.45, etc and find the value that results for the other value. Continue until a match occurs.

35.5.0.2 - Laser Measurements of Relative Distance

• In this application, the movable mirror is attached to some test piece. If it moves towards or away, then the detector will see pulses.



35.5.0.2.1 - Practice Problems

1. Show that the distance between two interference fringes is related to the change in height by calculating path distances.

35.6 GAUGE BLOCKS

• The purpose of gauge blocks are to provide linear dimensions known to within a given tolerance.

• The requirements of gauge blocks are,
  - the actual size must be known
  - the faces must be parallel
  - the surface must have a smooth finish
  - the surfaces must be flat

• most gauge blocks are made by normal techniques, but the high accuracy is obtained by a process called lapping (discussed later)

• The materials gauge blocks are made from are selected for,
  - hardness
  - temperature stability
  - corrosion resistance
  - high quality finish

• type of gauge blocks
  - rectangular
  - hoke (square)

• there are four grades of blocks,
  - reference (AAA) - high tolerance (± 0.00005mm or 0.000002”)
  - calibration (AA) (tolerance +0.00010mm to -0.00005mm)
  - inspection (A) (tolerance +0.00015mm to -0.0005mm)
  - workshop (B) - low tolerance (tolerance +0.00025mm to -0.00015mm)

• Original gauge block sets had lower tolerances and had a total of 91 pieces with values,
  0.010” to 0.100” in 0.001” steps

• An 81 piece set of gauge block was developed by Johansson(s??) and is capable of covering wider ranges of dimensions.
  0.1001” to 0.1009” in 0.0001” steps
  0.1010” to 0.1490” in 0.0010” steps
  0.0500” to 0.9500” in 0.0500” steps
  1.0000”, 2.0000”, 3.0000”, 4.0000” blocks
  (2 wear blocks at 0.0500”)

• An 83 piece set has also been developed and it has the values (in inches),

<0.001” divisions

0.1001	0.1002	0.1003	0.1004	0.1005	0.1006	0.1007	0.1008	0.1009

0.001” divisions

0.101	0.102	0.103	0.104	0.105	0.106	0.107	0.108	0.109	0.110
0.111	0.112	0.113	0.114	0.115	0.116	0.117	0.118	0.119	0.120
0.121	0.122	0.123	0.124	0.125	0.126	0.127	0.128	0.129	0.130
0.131	0.132	0.133	0.134	0.135	0.136	0.137	0.138	0.139	0.140
0.141	0.142	0.143	0.144	0.145	0.146	0.147	0.148	0.149	

0.05” divisions

0.050	0.100	0.150	0.200	0.250	0.300	0.350	0.400	0.450	0.500
0.550	0.600	0.650	0.700	0.750	0.800	0.850	0.900	0.950	

1” divisions

1.000	2.000	3.000	4.000

two 0.050” wear blocks

- The metric set has 88 gauge blocks (in mm),

<0.01mm divisions

1.001	1.002	1.003	1.004	1.005	1.006	1.007	1.008	1.009

0.01mm divisions

1.01	1.02	1.03	1.04	1.05	1.06	1.07	1.08	1.09	1.10
1.11	1.12	1.13	1.14	1.15	1.16	1.17	1.18	1.19	1.20
1.21	1.22	1.23	1.24	1.25	1.26	1.27	1.28	1.29	1.30
1.31	1.32	1.33	1.34	1.35	1.36	1.37	1.38	1.39	1.40
1.41	1.42	1.43	1.44	1.45	1.46	1.47	1.48	1.49	

0.5mm divisions

0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0
5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	

1cm divisions

10	20	30	40	50	60	70	80	90

two 2mm wear blocks

- Most gauge block sets include thin wear blocks that should be included at the ends of a gauge block stack to protect the other gauge blocks.

- How to select gauge blocks for an application from the 81 piece set above, build a stack that is 2.5744”

```
 2.5744”
-0.1004”
--------
 2.4740”
-0.1000”
--------
 2.3740”
-0.1240”
--------
 2.2500”
-0.2500”
--------
 2.0000”
-2.0000”
--------
      0”
```

therefore the gauge blocks are,

0.1004”
2 wear blocks @ 0.0500”
0.1240”
0.2500”
2.0000”

• To assemble a gauge block stack,

1. remove the gauge blocks required from the protective case
2. clean of the oil that they have been coated in using a special cleaner. It is acceptable to handle the blocks, in fact the oil from your hands will help them stick together.
3. one at a time, hold the blocks so that the faces just overlap, push the blocks together, and slide them until the faces overlap together. This will create a vacuum between the blocks that makes them stick together (this process is known as wringing).
4. Make required measurements with the gauge blocks, being careful not to damage the faces
5. take the blocks apart, and apply the protective coating oil, and return them to their box.

• When using gauge blocks, minimze the number used. Each block will have tolerance errors, and as the stack of blocks becomes larger, so does the error.

• Do not leave gauge blocks wrung together for long periods of time.

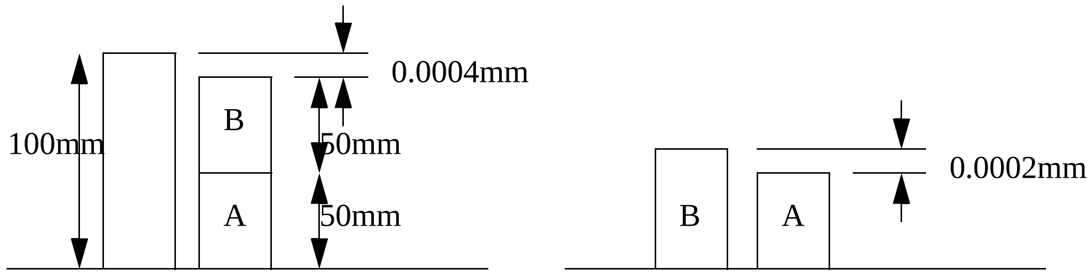
35.6.1 Manufacturing Gauge Blocks

• The basic sequence of operations is,

1. machine to basic size
2. harden blocks and stress relieve
3. grind to size
4. lap (8 blocks at a time) to obtain tight tolerance

• Johansson’s procedure to make the first set (????)

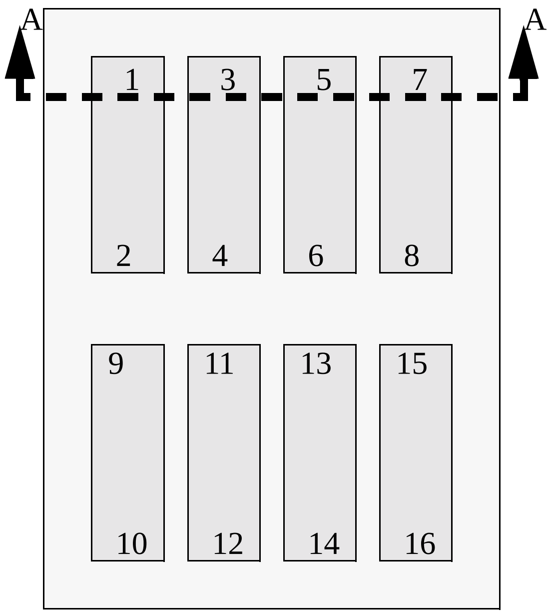
1. make a block with a 100mm length
2. Make two 50mm blocks
3. Determine the actual size of the 50mm blocks by comparing the difference in height



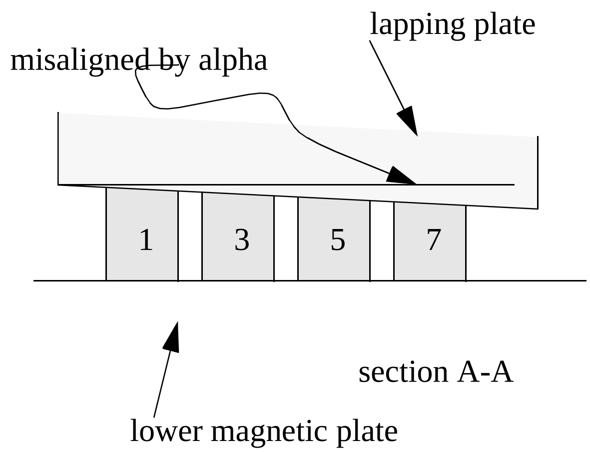
A + B = 100 - 0.0004 = 99.9996mm
A - B = -0.0002mm
2A + B - B = 99.9996 - 0.0002 = 99.9994mm
A = 49.9947mm
B = 49.9949mm

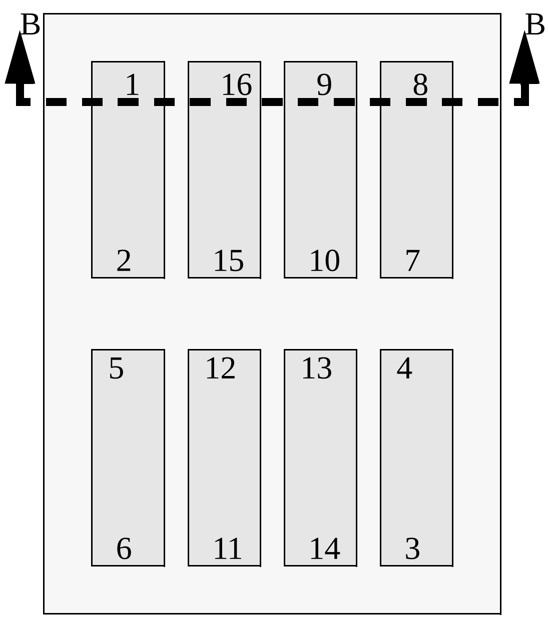
• Lapping is basically,

1. a porous pad is charged with a find grit powder. the excess powder is removed.
2. the parts to be lapped are secured to a surface plate magnetically (The positions are as shown below.
3. the lapping plate is placed on the block, and moved about, wearing down the blocks.
4. the lapping plate is removed, and the blocks are repositioned on the surface plate (as shown below) and the process is repeated.
5. The blocks are removed from the surface plate, and now are generally the same height.

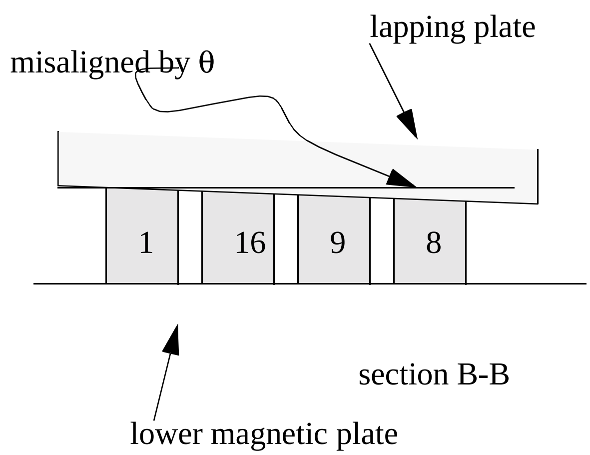


In the first lap, there are 8 blocks magnetically attached to the surface plate. The result is that the blocks take on a slight angle as shown below for a few of the blocks.





The blocks are rearranged, and the lapping process begins again. The figure below shows how rearranging the blocks in the manner shown will wear down the peaks.



- As each stage of lapping is done, the blocks become more even in size, and the lapping plate become more parallel with the lower plate.

• Next, knowing the gauge blocks are all very close in size, the stack of 8 blocks are wrung together into one pile, and compared to the master block using a comparator. The difference in heights, divided by eight, is the error in each block.

35.6.2 Compensating for Temperature Variations

• As gauge blocks change temperature, they also change size. The metals chosen for gauge blocks do resist this dimensional change, but will generally undergo some.

• The gauge block sets will carry dimensional readings, as well as rated temperatures. It is advised that all readings be taken at these temperatures, but if this is not possible, then some estimate of the dimensional change can be done.

• Basically this is done by using the difference between specified measurement temperature, and actual measurement temperature. This difference is multiplied by the coefficient of linear thermal expansion to give the change in size. This is obviously for small changes in temperature.

• Typical coefficients of linear thermal expansion is,

Steel 9.9 - 13.0 * 10^{-6} in./(in.°C) (typical is 11.5)
Bronze 16.7 * 10^{-6} in./(in.°C)
Aluminum 23.0 * 10^{-6} in./(in.°C)
Chrome carbide 8.4 *
Tungsten carbide 4 *
Cervit (?) -0.2 *

• Note the units are also ppm/°K

35.6.2.1 - References

Doiron, T., NIST, Personal Correspondence.

35.6.3 Testing For Known Dimensions With Standards

• When a dimension is well known, it can be measured by comparison to standards, using high precision, but limited range comparison instruments.

• Most gage blocks are steel which has a non-trivial coefficient of thermal expansion. But, considering that many parts are made of steel, these blocks will expand at approximately the same rate as the parts, and therefore no temperature compensation is required.

- If the gage blocks are made of the same material as the parts temperture compensation is less significant.

- For high accuracy measurements we want to allow temperatures of gages and parts to stabilize.

- The ISO 1 and ANSI Y14.5 standards speify a typical dimensional ambient temperature as 20°C.

- Materials may vary widely from the listed coefficient of thermal expansion. As a result it is best to take them to 20±0.1°C for high precision measurements, and 20±0.01°C for critical measurements.

35.6.3.1 - References

Doiron, T., NIST, Personal Correspondence.

35.6.4 Odd Topics

- There are also a number of angular gauge blocks for the measurement of angles. The two common sets are,

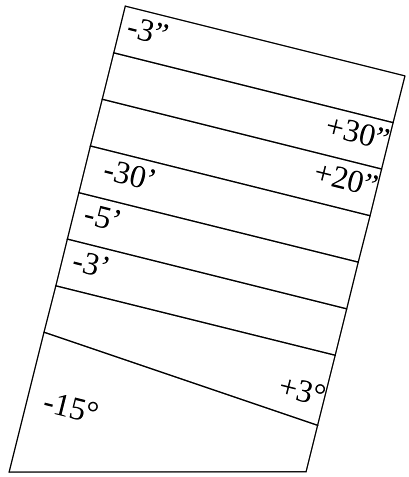
16 piece set		
	degrees	45°, 30°, 15°, 5°, 3°, 1°
	minutes	30’, 20’, 5’, 3’, 1’
	second	30”, 20”, 5”, 3”, 1”
13 piece set		
	degrees	1°, 3°, 9°, 27°, 41°, 90°
	minutes	1’, 3’, 9’, 27’, 0.1’, 0.3’, 0.5’

tool room accuracy ±1 second
laboratory accuracy ± 0.25 seconds

- The selection of angular gauge blocks is similar to the selection of linear gauge blocks, except that subtration may also be required. (When the blocks are stacked, then angles are simply reversed.

For the angle 12°37’13”, find the angular gauge block stack using the 16 piece set.

12°37’13”
-3”
____
12°37’10”
+30”
____
12°37’40”
+20”
____
12°38’
-30’
____
12°8’
-5’
____
12°3’
-3’
____
12°
+3°
____
15°
-15°
____
0



35.6.5 Practice Problems

1. From the same set of gauge blocks build up the dimensions 3.2452” and 3.2462”. You must not use the same gauge blocks twice. Use the 83 piece gauge block set.

35.6.6 Limit (GO & NO GO) Gauges

• These gauges are made for simple pass/fail inspection

• Basically there are two separate, or combined gauges for each feature to be measured.

• One gauge must fit inside the feature, and the second must not. In other words the GO gauge must fit inside/outside the feature, the NO GO gauge must not. If the GO gauge does not fit, the tolerance is above the maximum metal tolerance. If the NO GO gauge goes, the feature is below the minimum metal tolerance.

• This method is best suited to unskilled operators testing many parts, although more modern quality methods suggest this procedure should be replaced with Statistical Process Control (SPC).

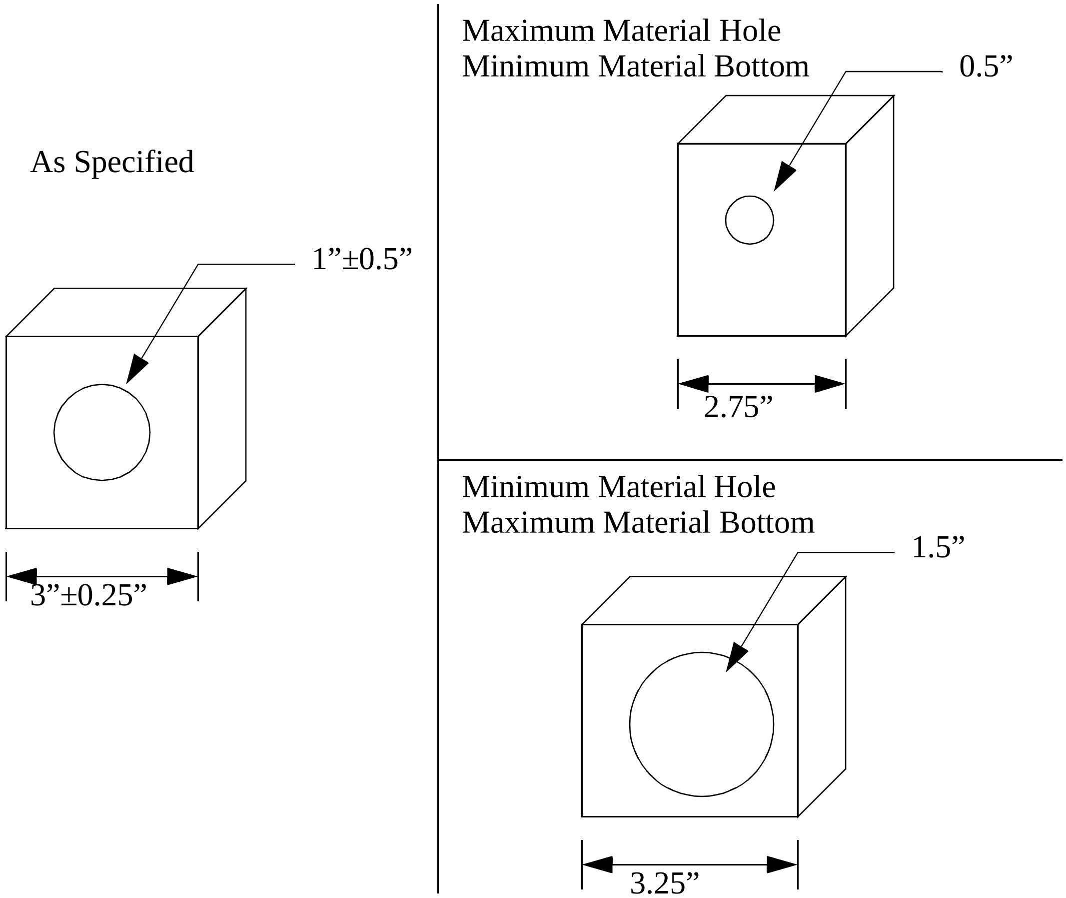
• This method can also be used for inspection rooms, and limited runs using gauge blocks.

35.6.6.1 - Basic Concepts

• The GO gauge is made near the maximum metal condition. The GO gauge must be able to slip inside/over the feature without obstruction.

• The NO GO gauge is made near the minimum metal condition. The NO GO gauge must not be able to slip inside/over the feature.

• The terms minimum metal condition, and maximum metal condition are used to describe the tolerance state of a workpiece. If we assume (at least for now) that all parts are made by removing metal from larger pieces, then we are trying to remove a certain amount. If we are drilling a hole the maximum metal condition will be when the hole is small, and extra metal is ‘left behind’. The minimum metal condition would be when the hole has been overdrilled and as little metal as possible is left behind. The tolerances often set the acceptable maximum and minimum metal conditions. If features are external, the maximum metal condition is their largest size, and minimum metal condition is their smallest size.



• A basic set of shapes these typically deal with are,
  - plug
  - ring
  - taper
  - snap
  - threads

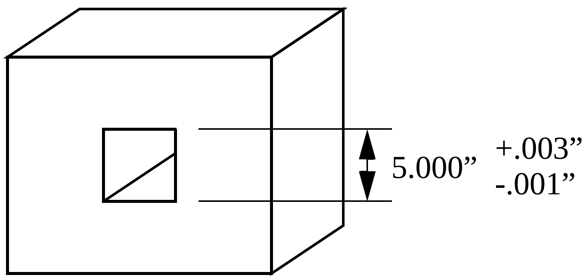
• These are good for work tolerances down to about 0.002” (anything less should use comparators)

35.6.6.2 - GO & NO GO Gauges Using Gauge Blocks

• Simple GO & NO GO gauges for internal features can be made from gauge blocks.

• The basic procedure is,
  1. Determine the dimension and tolerance of the feature to be tested.
  2. Check the temperature of the measurement environment.
  3. Determine the upper/lower dimensional limits

4. If the gauge blocks are not being used at the rated temperature, adjust the dimensions.
5. Determine the gauge block stacks for both the GO and NO GO gauges.
6. Test.



Given:
If the Part is aluminum the coefficient of linear thermal expansion is
C = 0.0000127°F in./in.
Assume the coefficient for the gauge blocks is C = 0.0000061°F in./in.
The temperature in the measurement room is 76°F.
The rated temperature for the gauge blocks is 64°F.

The maximum metal dimension is 5.000-0.001 = 4.999” for the GO gauge.
The minimum metal dimension is 5.000+0.003 = 5.003” for the NOGO gauge.

Find the needed change in the gauge block size as a result of the temperature difference.

$$\Delta L = (\Delta T)(\Delta C)(L)$$
$$\therefore \Delta L = (76 - 64)(0.0000127 - 0.0000061)(5.000\text{in.})$$
$$\therefore \Delta L = 0.0005\text{in.}$$

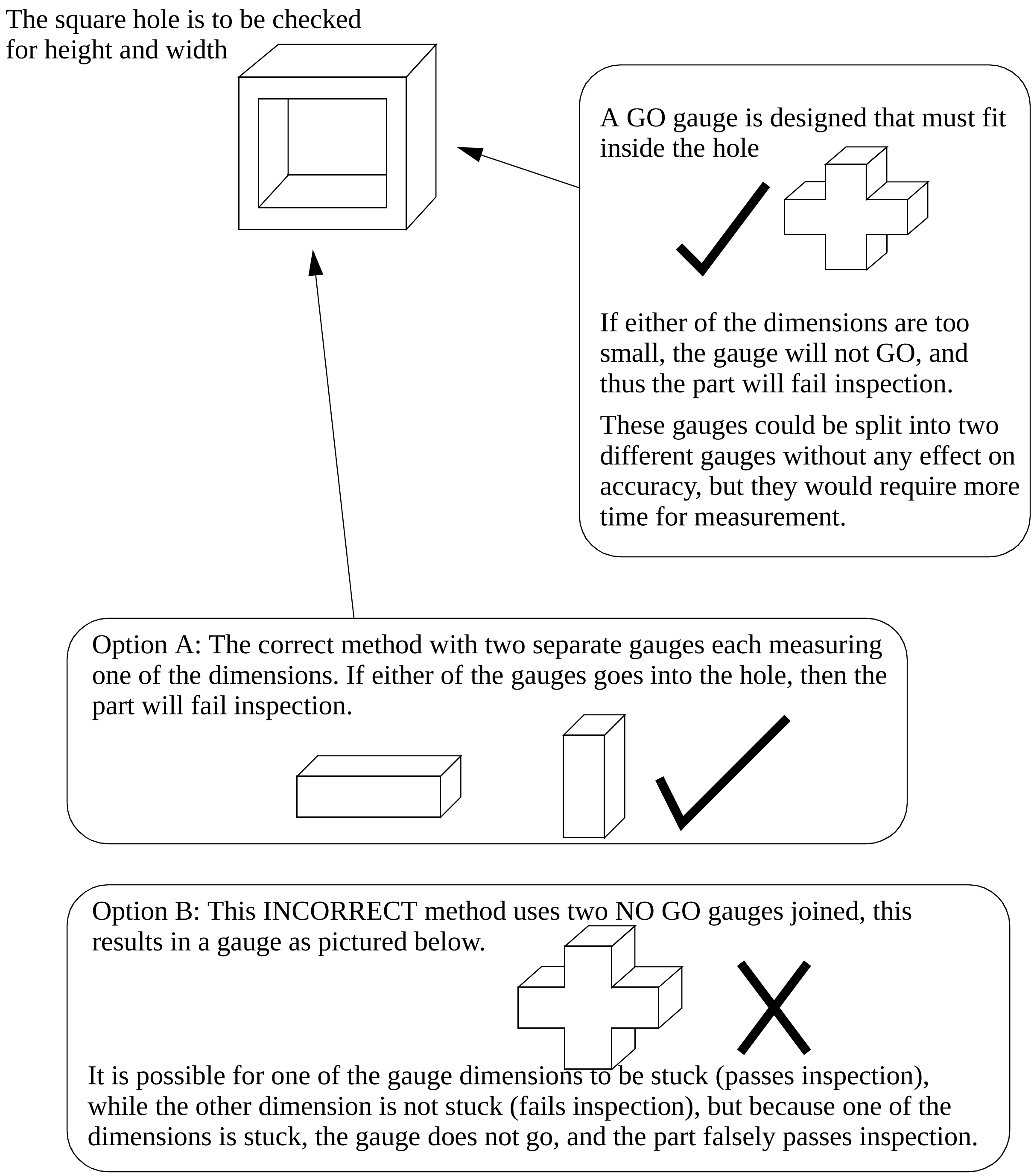
The new size for the GO gauge is 4.999”+0.0005” = 4.9995”
The new size for the NO GO gauge is 5.003”+0.0005” = 5.0035”

Make up the gauge block stacks. (Note when two stacks are taken from the same set, some planning will be required not to use the same block twice.)

35.6.6.3 - Taylor’s Theory for Limit Gauge Design

1. GO gauges should check all features for maximum metal condition at one time
2. NO GO gauges should check only one feature at a time for minimum metal condition

• The example below should illustrate the two points,

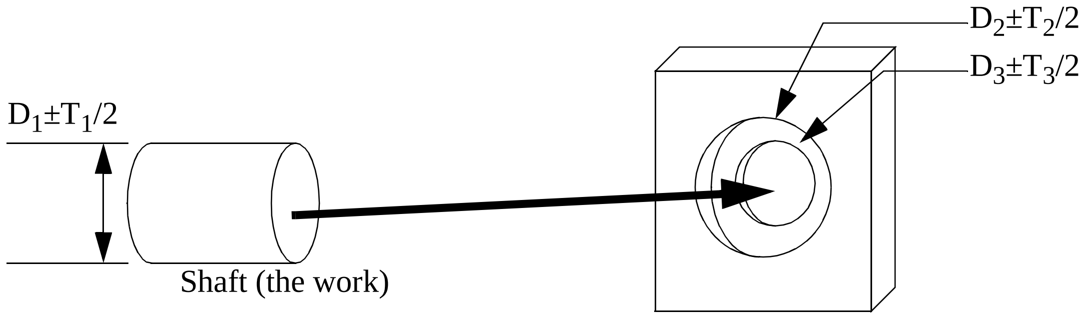


35.6.6.4 - Gauge Maker's Tolerances

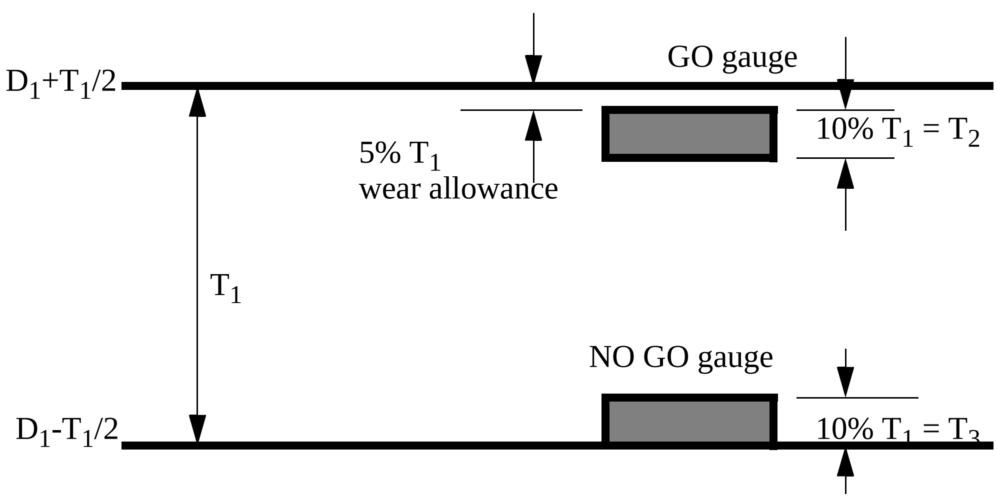
• Because gauges have to be manufactured themselves, they must also have tolerances asigned.

• The Unilateral System is very popular,
1. A general tolerance is applied to both GO & NO GO gauges of 10% of the work tolerances
2. If work tolerances are above 0.0035”, a wear allowance of 5% of the work tolerance is added to the GO gauge only
3. All gauge tolerances are made to fall within the work tolerance zones. The effect is that the gauges will always be between the maximum tolerance limits, and no bad parts should be accepted. The only downside is that some good parts will also be rejected.

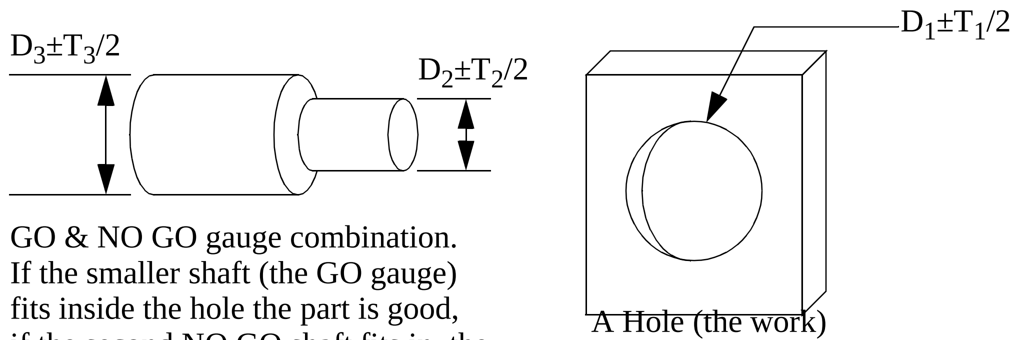
• An example of the Unilateral Tolerance System applied to GO & NO GO gauges is given below, as applied to a shaft (here we are measuring external features). The gauge shown is a gap and ring gauge.



D_1, T_1 = The shaft diameter, and tolerance specified by the designer
D_2, T_2 = The GO gauge diameter and tolerance
D_3, T_3 = the NO GO gauge diameter and tolerance

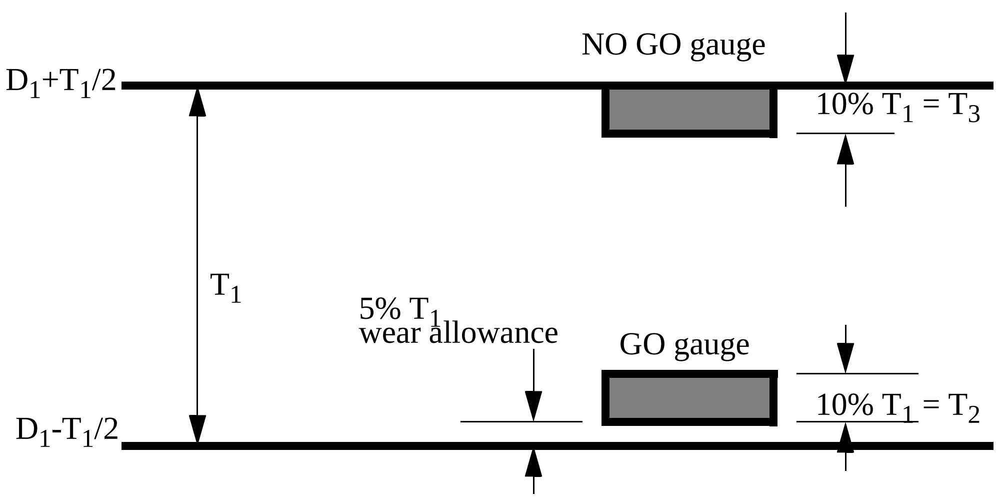


• We can also look at an example of a hole that is to be measured with GO & NO GO gauges (an internal feature). The gauge shown is a Plug Gauge.



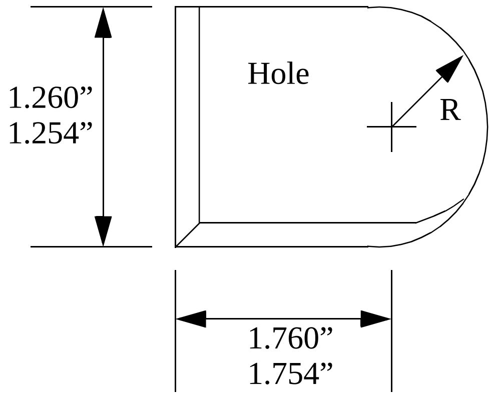
GO & NO GO gauge combination.
If the smaller shaft (the GO gauge) fits inside the hole the part is good, if the second NO GO shaft fits in, the part is rejected.

D_1, T_1 = The hole diameter, and tolerance specified by the designer
D_2, T_2 = The GO gauge diameter and tolerance
D_3, T_3 = the NO GO gauge diameter and tolerance



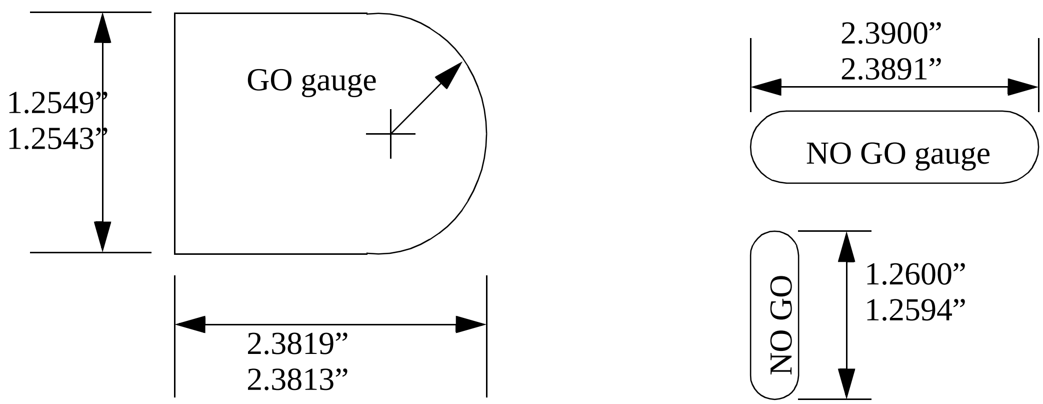
35.6.6.4.1 - Sample Problems

1. Design Plug gauges for holes that are 1.500” +0.0025” - 0.000”.
2. Design a gap gauge to inspect shafts that are 0.875” +0.000” -0.008”.
3. Design GO and NO GO gauges for the hole shown below.



4. Design GO/NO GO gauges for an equilateral triangular hole that is to have each side 2.025”±0.002”.

ANSWERS:
1. (ans. GO limits are 1.50025”/1.5000” dia., NO GO limits are 1.50250”/1.50225” dia.)
2. (ans. GO limits are 0.8746”/0.8738” dia., NO GO limits are 0.8678”/0.8670” dia.)
3. (ans. the three gauges are pictured below)

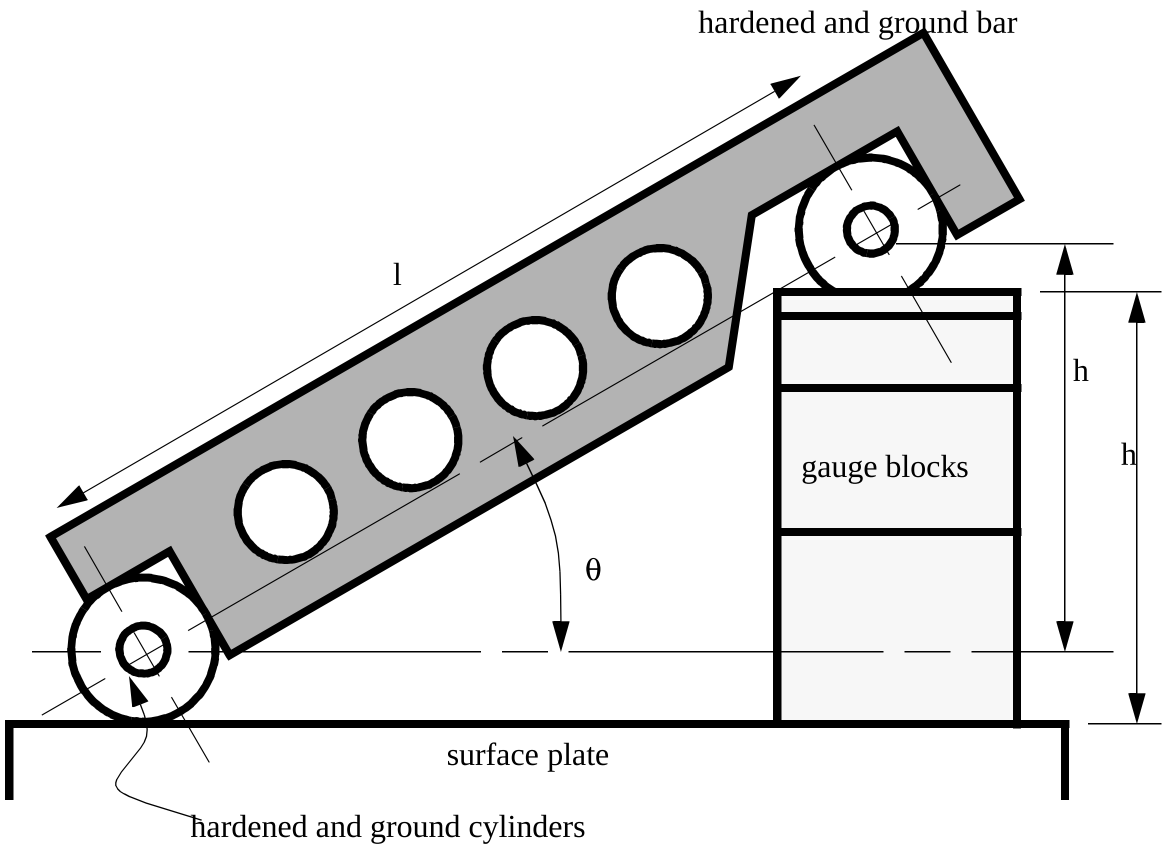


35.6.7 Sine Bars

• When a reference for a non-square angle is required, a sine bar can be used.

• Basically a sine bar is a bar of known length. When gauge blocks are placed under one end, the sine bar will tilt to a specific angle.

• The figure below shows a sine bar from the side,



l = distance between centres of ground cylinders (typically 5” or 10”)
h = height of the gauge blocks
θ = the angle of the plate

$$\boxed{\theta = \operatorname{asin}\left(\frac{h}{l}\right)}$$

• A simple example is - set up a sine bar with an angle of 24°-57’, if the sine bar has 5” centres.

$$\sin\left(24 + \frac{57}{60}\right) = \frac{h}{5.000}$$

$$\therefore h = 2.1091 \text{ inches}$$

continue on and calculate the gauge blocks required......

• The sine bar shown above will only allow a single angle to be set, but in some cases we want to set two angles, for this a compound sine plate is used.

35.6.7.1 - Sine Bar Limitations

- When using a sine bar, the height setting is limited by the gauge block divisions available (often 0.0001”). This results in an error that may be negligible, or in some cases quite significant.
- A simple example to illustrate this effect is given below for two extreme cases. In the first case the sine bar is near horizontal, in the second case it is near vertical. Assuming a sine bar with 10” centres, and two angles of 1°-30’ and 88°-00’, and that an 84 piece gauge block set is used.

ASIDE:

$$\text{SENSITIVITY} = \frac{\Delta\text{OUT}}{\Delta\text{IN}} \qquad \theta = \operatorname{asin}\left(\frac{h}{r}\right)$$

$$\therefore \Delta\text{IN} = \Delta h$$

$$\therefore \Delta\text{OUT} = \Delta\theta = \text{etc}$$

Therefore, as the angle approaches 90°, the error increases

First, find the gauge block heights required,

$$h_1 = 10\sin\left(1 + \frac{30}{60}\right) = 0.2618\text{in.} \qquad h_2 = 10\sin(88) = 9.9939\text{in.}$$

Next, find the gauge block heights,

******* DO IN CLASS

Given the actual heights, we can recalculate the actual angle of the sine bar,

$$\theta_{A1} = \operatorname{asin}\left(\frac{h_1}{10}\right) = \qquad \theta_{A2} = \operatorname{asin}\left(\frac{h_2}{10}\right) =$$

This shows the errors of the two angles

$$\theta_{error1} = \qquad \theta_{error2} =$$

***Note: the error for the larger angle is also much larger

• In any of these cases we can see that at larger angles, the sine bar is susceptible to errors in the length of the sine bar, as well as in the height of the gauge blocks.

35.6.7.1.1 - Practice Problems

1. Determine what height is required to set up a 5” sine bar for an angle of 11°34’. Specify the gauge block stack required.

2. Why are different grades of gauge blocks used?
ans. There are different quality levels for gages blocks. The poorest sets are workshop grade and are more accurate than most machine tools. The best sets are very accurate, and must be kept in tightly controlled conditions. The bast sets are used for calibrating others.

3. How are a ring gauge and a plug gauge different?
ans. A plug gage goes into a hole, a ring gage surrounds a dimension.

35.6.8 Comparators

• Accuracies commonly below 1/10 thousandth of an inch

• These instruments try to reduce the friction that is such a problem for the dial indicators

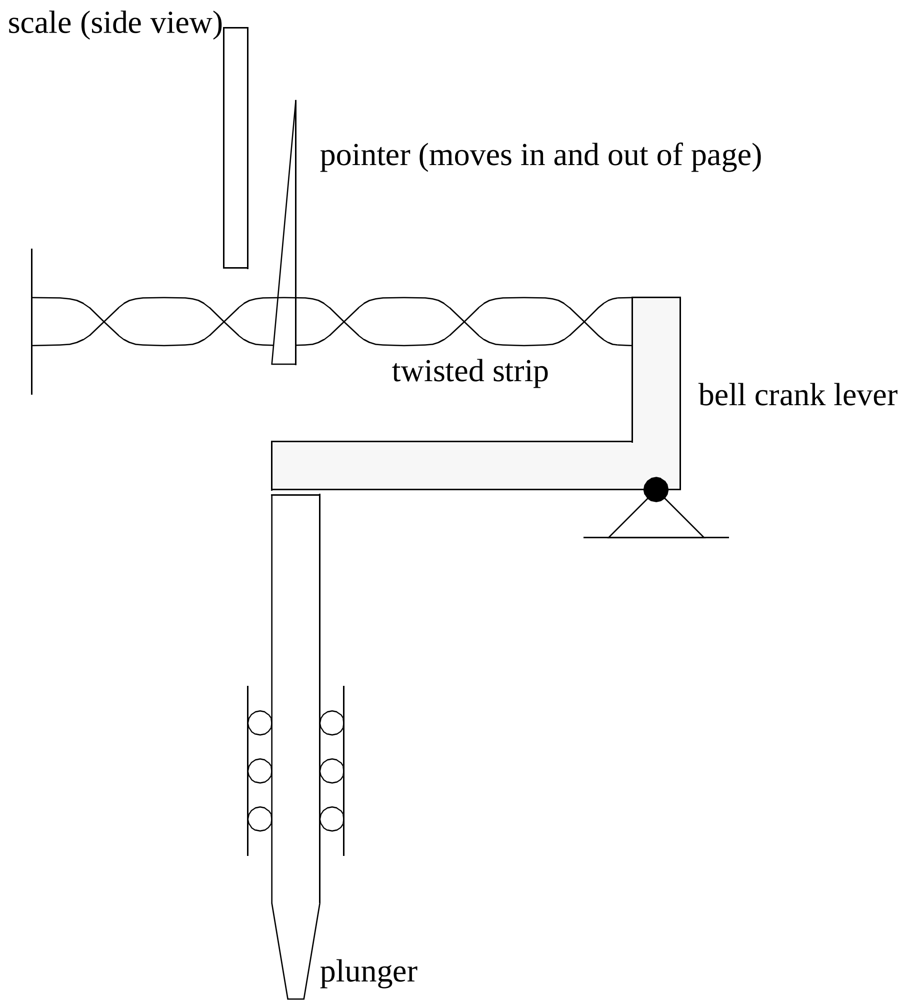
• There are four common principles used to design these instruments,
- mechanical
- pneumatic
- electrical
- optical

• comparators have very limited ranges of motion, but very high sensitivities (and therefore accuracies). As a result the comparators are often calibrated against standards such as gauge blocks.

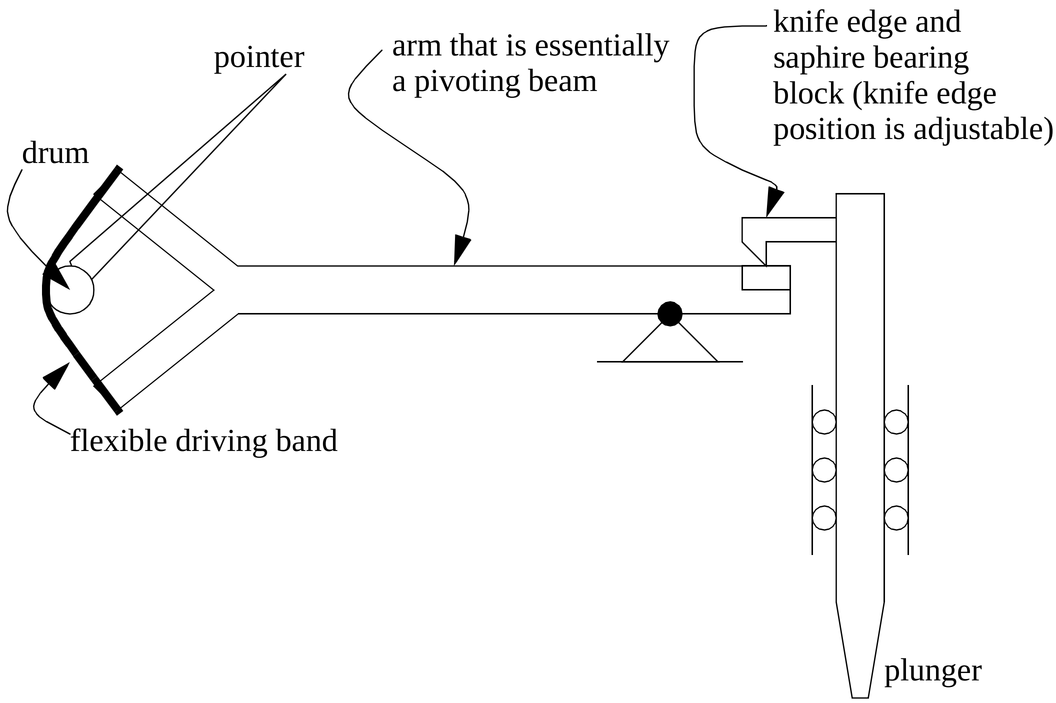
• The basic requirements of these instruments are,
- rigidity of the design
- linear magnification within the operation range
- coarse and fine offset adjustments

35.6.8.1 - Mechanical Comparators

• The Johansson Mikrokator used a twisted strip with a pointer attached. as the plunger is depressed, it causes the strip to stretch. As the twisted strip is stretched, it changes the angle of the pointer, and thus the indicated deflection.

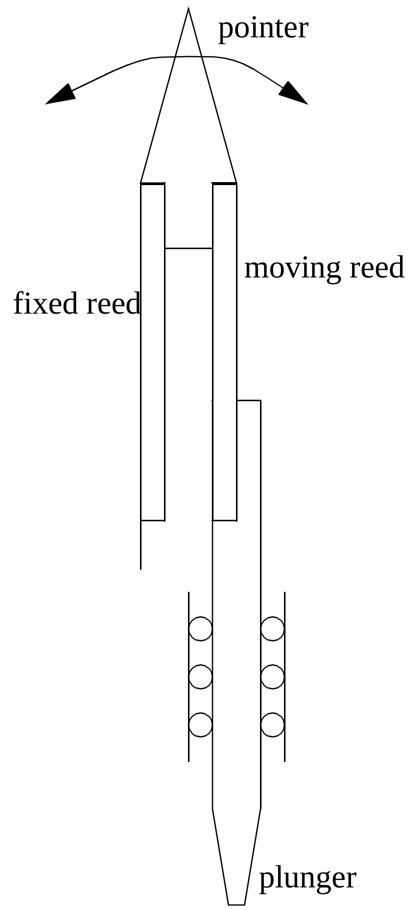


• The Sigma Mechanical Comparator uses a partially wrapped band wrapped about a driving drum to turn a pointer needle.



35.6.8.2 - Mechanical and Optical Comparators

• The Eden-Rolt Reed system uses a pointer attached to the end of two reeds. One reed is pushed by a plunger, while the other is fixed. As one reed moves relative to the other, the pointer that they are commonly attached to will deflect.



35.6.8.3 - Optical Comparators

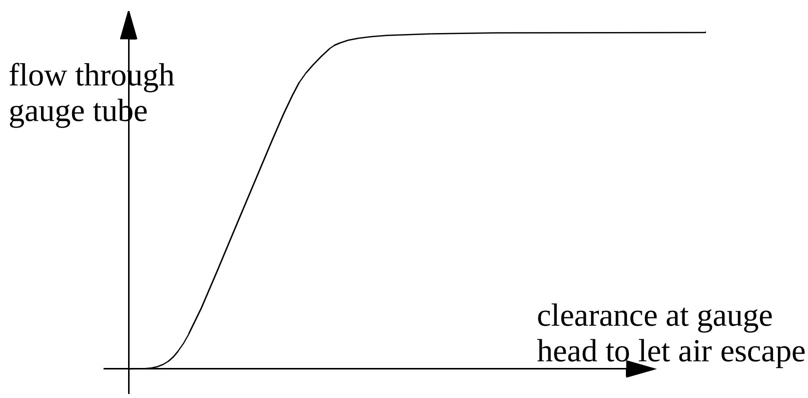
• These devices use a plunger to rotate a mirror. A light beam is reflected off that mirror, and simply by the virtue of distance, the small rotation of the mirror can be converted to a significant translation with little friction.

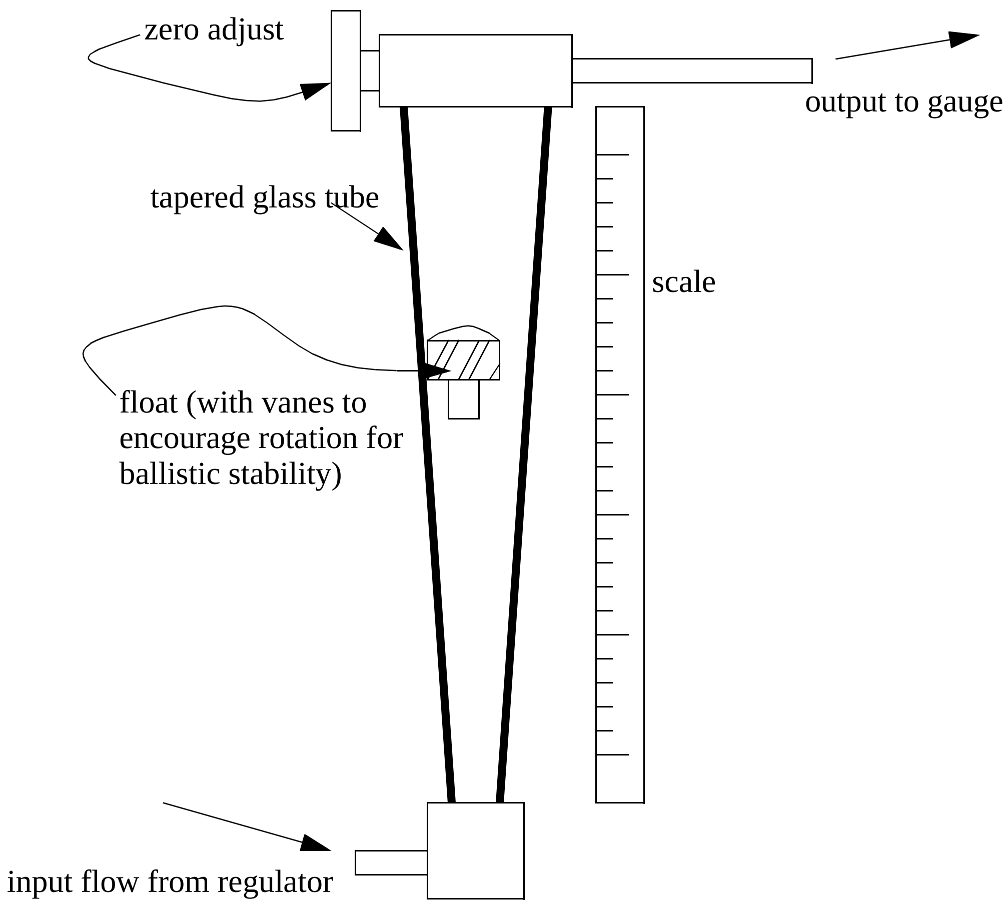
XXXXXXXXXXXXXXXX

35.6.8.4 - Pneumatic Comparators

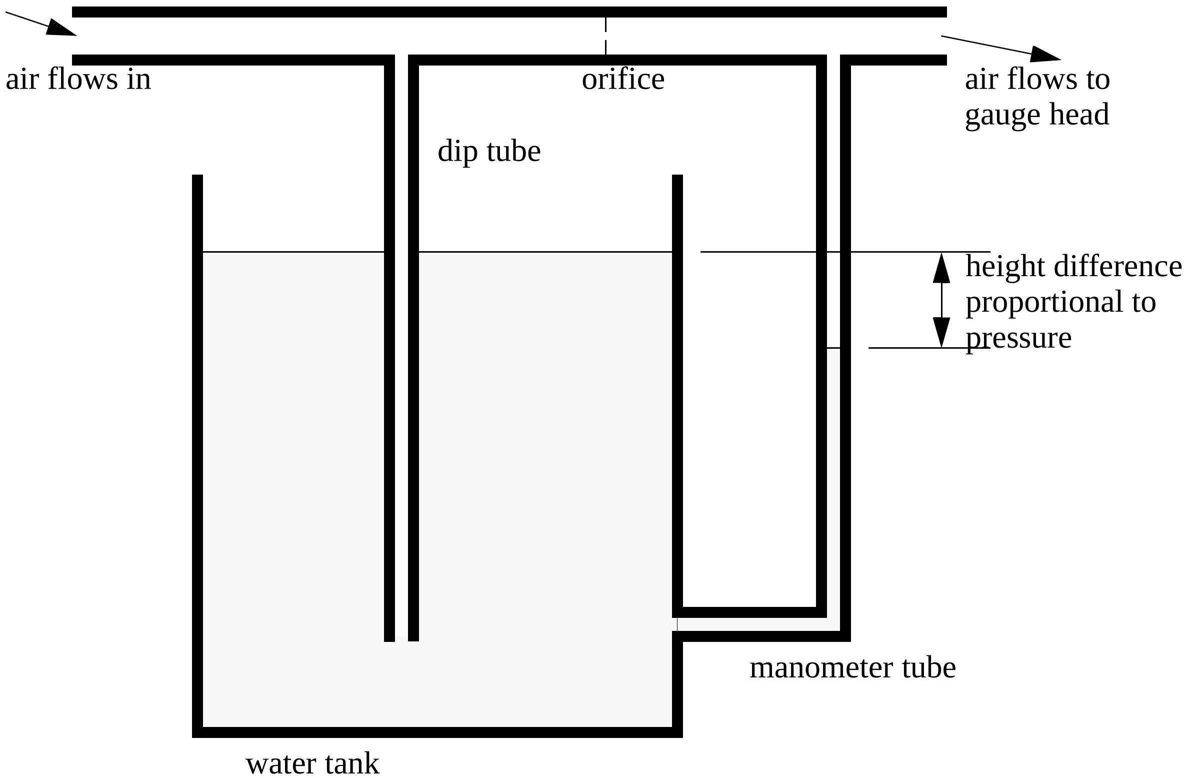
• Flow type
  - the float height is essentially proportional to the air that escapes from the gauge head
  - master gauges are used to find calibration points on the scales
  - the input pressure is regulated to allow magnification adjustment

- a pressure bleed off valve allows changes to the base level for offset
- The pressure is similar to that shown in the graph below,





• The Soloflex Back Pressure System uses an orifice with the venturi effect to measure air flow. If the gas is not moving, the pressure on both sides of the orifice will be equal. If the flow is moving quickly, the air pressure on the downstream side of the orifice will be at a lower pressure.



• A Differential Back Pressure system uses a split flow channel, one flow goes to the gauge head, the other goes to a zero offset valve. A meter measures the difference in pressures, and thus gives the differences in pressure.

35.6.9 Autocollimators

35.6.10 Level Gauges

35.6.10.1 - Clinometer

35.6.10.2 - The Brookes Level Comparator

35.6.11 The Angle Dekkor

• Measures surface flatness using collimated light, and a moving lens to focus the beam as it travels across the test surface.

35.7 MEASURING APARATUS

35.7.1 Reference Planes

• Very flat surfaces are needed when setting up height or angle measurements. This is because the measuring instruments are moved across the surface, and if the height varies, accuracy will suffer.

• Typical plates are made from cast iron, or granite, and are from a few inches per side, and up. A typical plate might be 2 feet by 2 feet.

35.7.1.1 - Granite Surface Plates

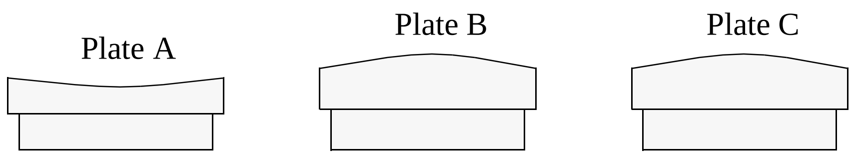
• The surfaces are finished by rotary lapping machines.

• When done the flatness of the surfaces are inspected for flatness. This is done with auto-collimators or laser alignment equipment followed by geometrical analysis oncomputer.

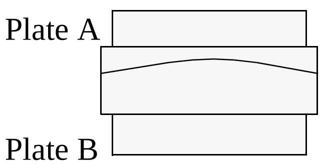
• The general advantages of these plates over cast iron are,
  - durability
    - closer tolerances
    - lower cost
    - lower thermal expansion
  - quality
    - non-rusting
    - burrs do not occur, but chipping does
  - ease of use
    - non-magnetic
    - less glare
    - no oil is required, thus dust does not stick
    - less wringing
    - inserts are often provided for clamping

35.7.1.2 - Cast Iron Surface Plates

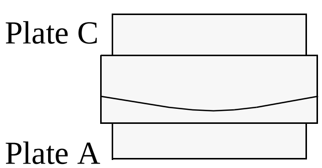
• Whitworth’s three plate method of manufacture is outlined below. This method is particularly desirable because the flatness is self generating.



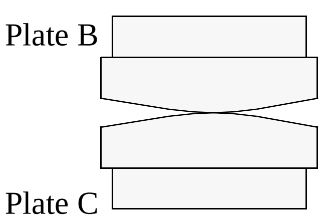
Three plates are shown (with exaggerated curves in the surface). These plates will be hand scraped in alternate combinations to reduce the surface curvature. As the process continues, the plates will become flatter.



Step 1:
plates A and B are scraped.



Step 2:
Plate ‘C’ is scraped to match ‘A’



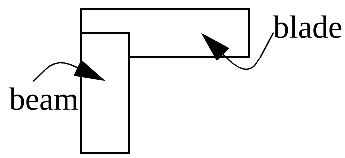
Step 3:
The process is repeated by scraping ‘B’ and ‘C’.
This reveals errors, and reduces error.

***NOTE: Plate ‘A’ is the master plate

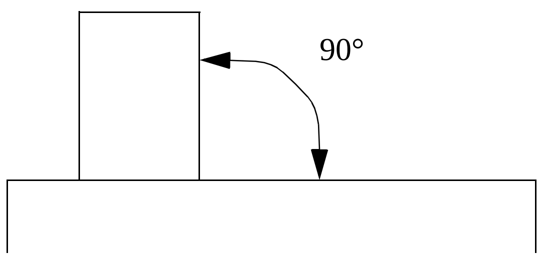
35.7.2 Squares

• Squares use known angles as a measurement reference. Generally a square is used to measure 90 degree angles (i.e., square corners)

• The basic types are,
  - Combination Set - This has a sliding blade and is used for layout.
  - Standard Square - There are three grades: 1. Reference, 2. Inspection, 3. Workshop



  - Toolmakers Square
  - Cylindrical Square



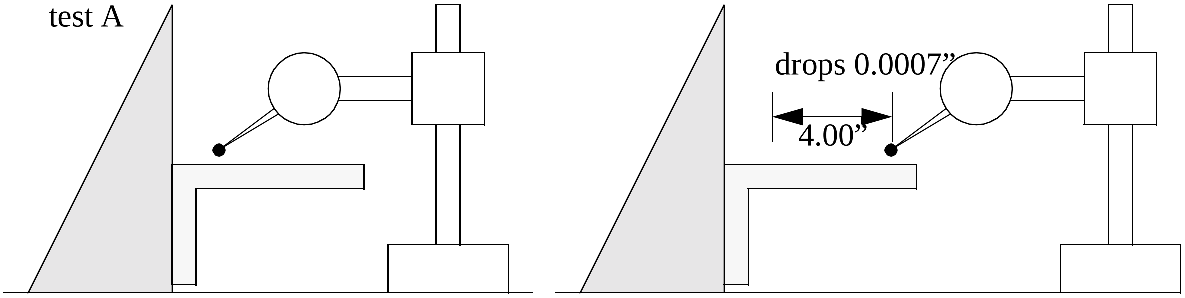
Both the object to be measured, and the square are placed on a reference plane. The square should provide and 90° angle to the reference plane.

  - Direct Reading Type

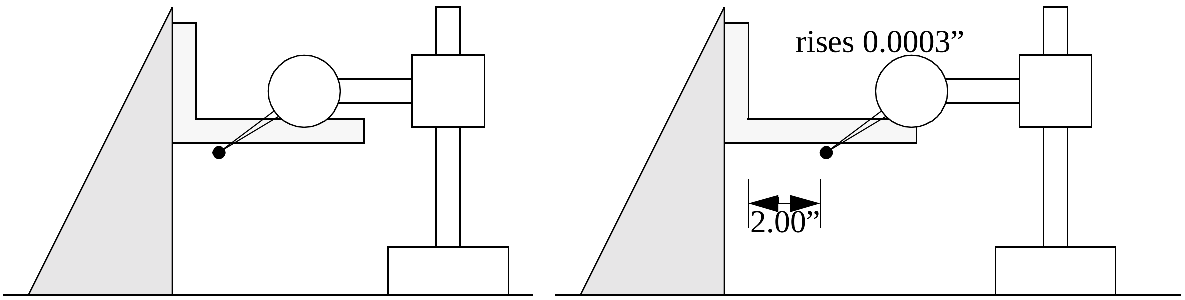
• The advantages of the Toolmakers, and cylindrical squares are,
  1. There is a line of contact between the part and the square.
  2. More resistant to damage.
  3. Can be checked by rotation.

• Standard Squares can be checked for errors using a reversal test. In this test an angle plate is placed on a reference plane, and a standard square is placed against the angle plate. A dial indicator is run along the square from one end to the other, and the drop/rise is measured. The square is now rotated so that the other side is now measured. The drop/rise in height can be used to calculate the angles of both the square, and the angle plate.

test A



test B: With the square reversed



Some values of drops, and distances are given above for illustration. The first step in calculating the angles is to find the angles in the first, and second tests.

$$\theta_A = \operatorname{asin}\left(\frac{-0.0007}{4.00}\right) = -0.010°$$

$$\theta_B = \operatorname{asin}\left(\frac{0.0003}{2.00}\right) = 0.009°$$

Based on these values, the angle of the square is,

$$\theta_{SQUARE} = 90° + \left(\frac{\theta_A - \theta_B}{2}\right) = 89.99°$$

Likewise, the angle of the angle plate is,

$$\theta_{ANGLE} = 90° + \left(\frac{\theta_A + \theta_B}{2}\right) = 90.00°$$

35.7.2.1 - Coordinate Measureing Machines

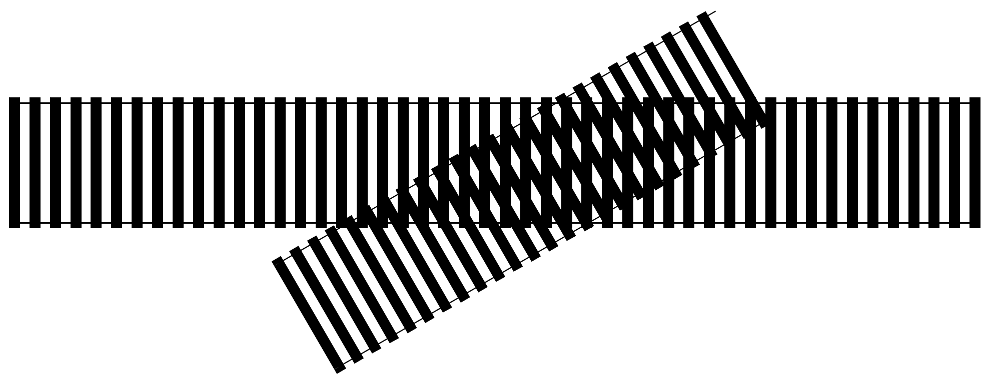
• generally measure x-y-z coordinates using touch probes

• these measurements can be made by positioning the probe by hand, or automatically in more expensive machines.

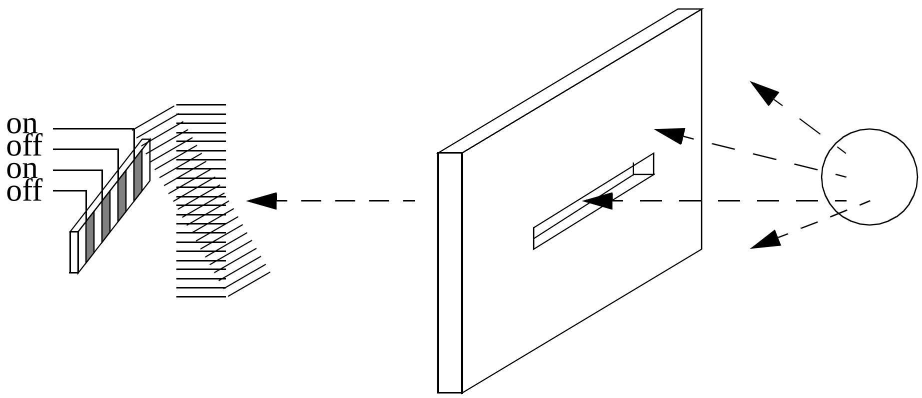
• reasonable accuracies are 5 micro in. or 1 micro metre.

• The method these machines work on is measurement of the position of the probe using linear position sensors. These are based on moire fringe patterns (also used in other systems).

1. The Pattern - two sheets with thin fringes are put at right angles, the optical effect is a darkened strip that runs along the strips. As one of the strips is moved the band will move up or down. When optically magnified the moving strip can be used to determine direction, and distance of motion.



2. The Detector - a collimated light source is shone upon the pattern. The light is then reflected back to a grid of sensors. The sensors then go on/off to indicate the presence of the band.



35.7.2.2 - Practice Problems

1. If Moire fringes are 1/4" in height and an array of 4 photocells are used to pickup the light patterns, how far apart would 50 micro in. wide lines have to be if the two patterns were at 45° angles?

2. Given that four measurements (x, y, z) were taken on a sphere, develop an expression to estimate a radius for the sphere, and an average error.

AM:35.7.3 Coordinate Measuring Machines (CMM)

• Automated machines used for inspection of parts

• Variety of methods for determining point locations in space,
  - touch sensors,
  - laser grids,
  - video cameras

• Advantages,
  - can automate inspection process
  - less prone to careless errors
  - allows direct feedback into computer system

• Disadvantages,

- costly
- fixturing is critical
- requires a very good tolerance model

36. ASSEMBLY

• the mating of parts to give a combined operation.

• In previous centuries, and before, fit in assemblies was often not considered, or when it did matter, each piece was custom fitted.

• Modern methods of mass production means that some fundamental methods of fitting are necessary.

• The three basic methods of fitting are,
  - Fitting - One part is made to size, and then a second part is made to fit it.
  - Selective Assembly - parts are made to loose general tolerances, and then the results are sorted into tolerance ranges. (e.g. bearings, solar cells, etc)
  - Interchangeable Assembly - Parts are made to tighter tolerances, and as a result assembly of randomly selected parts will yield a good fit. This is essential for modern assembly lines.

• The basic categories of fits are,
  - Clearance - a gap is always present between parts
  - Transitional - the parts will have a gap sometimes, other times the parts will touch
  - Interference - both parts will always be in full contact

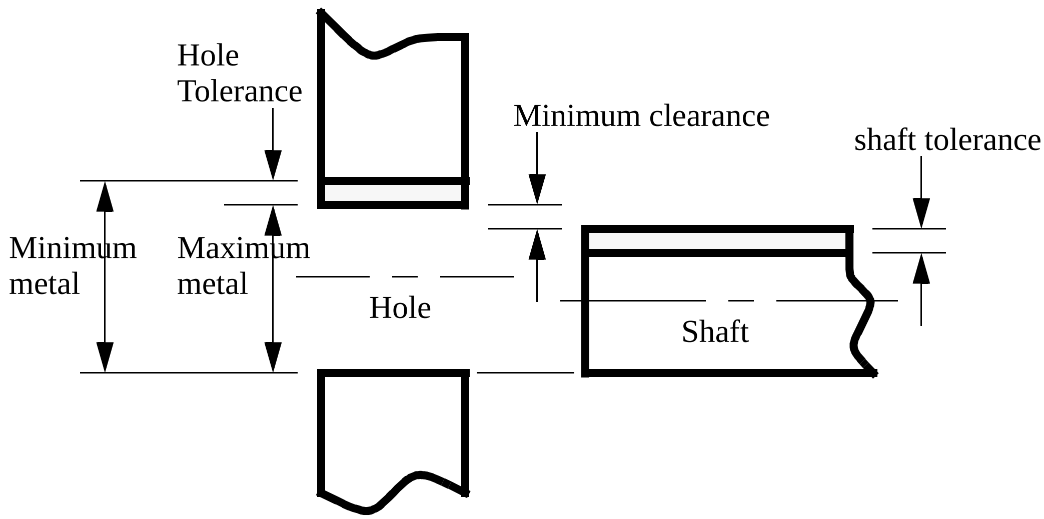
36.1 THE BASICS OF FITS

• A set of reasonable fits is suggested below,
  shafts rotating under 600 rpm with ordinary loads; >RC5
  shafts rotating over 600 rpm with heavy loads; < RC5
  shafts sliding freely; approx. LC
  push fits with keyed shafts and clamp, no fitting; LT
  parts assmemble with some basic fitting; LN
  Permanent assembly with no freely moving parts; FN1
  permanent assembly with severe loading effects; FN3
  permanent assembly with press needed for assembly; FN5

36.1.1 Clearance Fits

• A clearance fit always has a gap between the two mating parts.

• The diagram below shows a clearance fit between a shaft and a hole

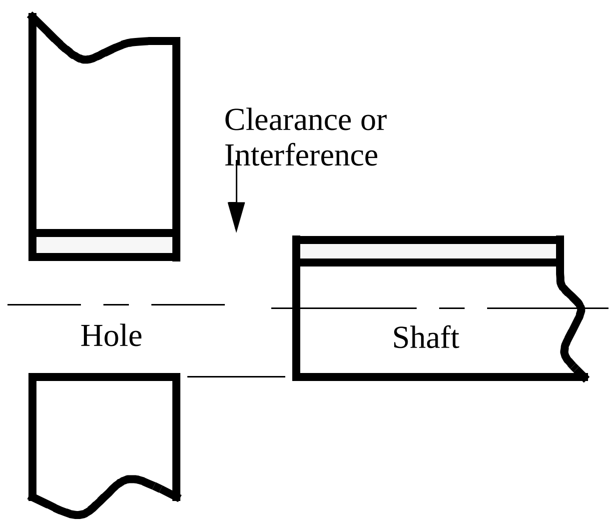


36.1.2 Transitional Fits

• This type of fit may result in interference, or clearance

• This type of fit can be used for items such as snap fits

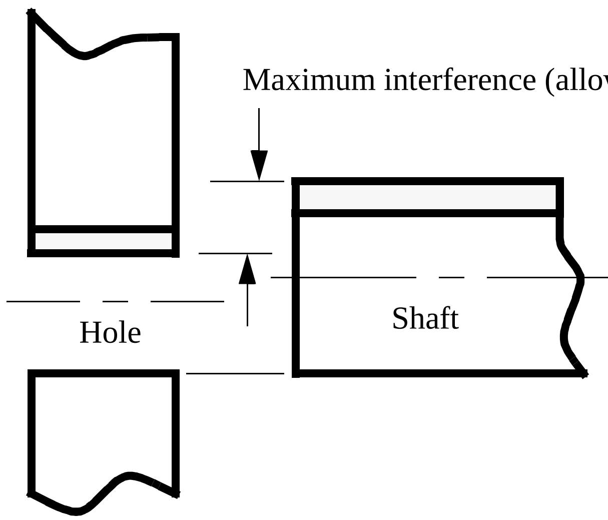
• The figure below illustrates this condition for a hole shaft pair



36.1.3 Interference Fits

• Interference fits always overlap and are used mainly for press fits where the two parts are pushed together, and require no other fasteners

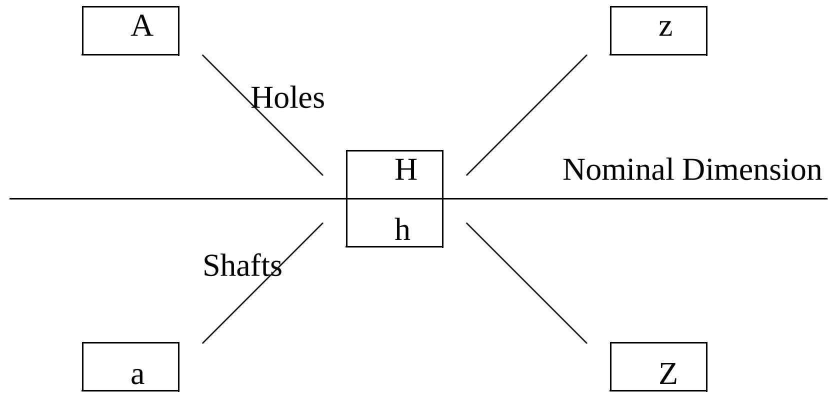
• The figure below shows an interference fit for a hole shaft pair



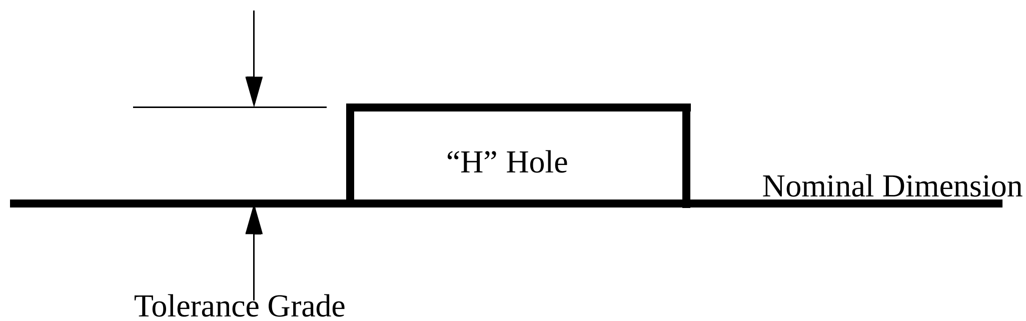
36.2 C.S.A. B97-1 1963 LIMITS AND FITS(REWORK)

• Five types of fits are allowed, with a variety of classes

CODE	DESCRIPTION	CLASSES
RC	RUNNING CLEARANCE	1 TO 9
LC	LOCATIONAL CLEARANCE	1 TO 11
LT	LOCATIONAL TRANSITION	1 TO 6
LN	LOCATIONAL INTERFERENCE	1 TO 6
FN	FORCE OR SHRINK	1 TO 5



• This system is hole based (it uses the “H” hole)



• There are 22 diameter steps from 0” to 200”

• A fit is classified as a grade of “H” hole and a grade of shaft

• For example,

Assume we are given an RC2 fit with a nominal diameter of 2.25”. (This may be determined during the design stage using experience, lookup tables, etc.).

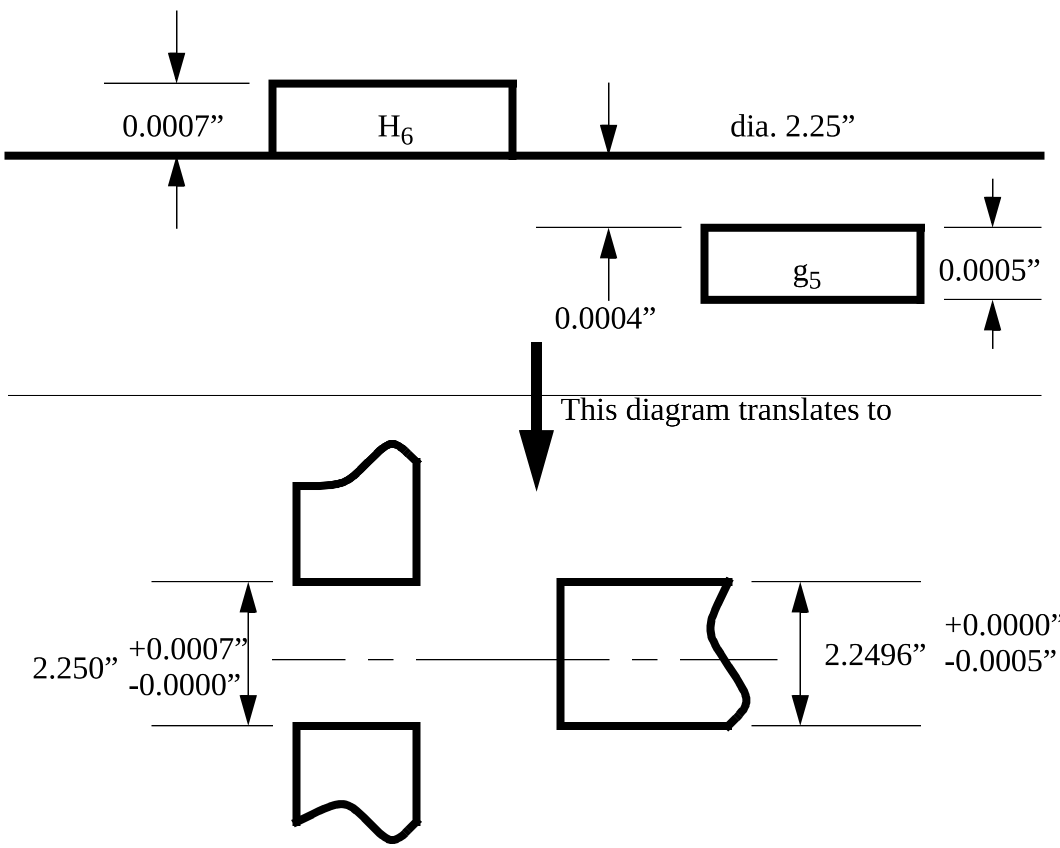
The RC2 specifies a Running Clearance - Class 2 fit which uses ISO hole H_6, and ISO shaft g_5.

The CSA tables (given later) provide,

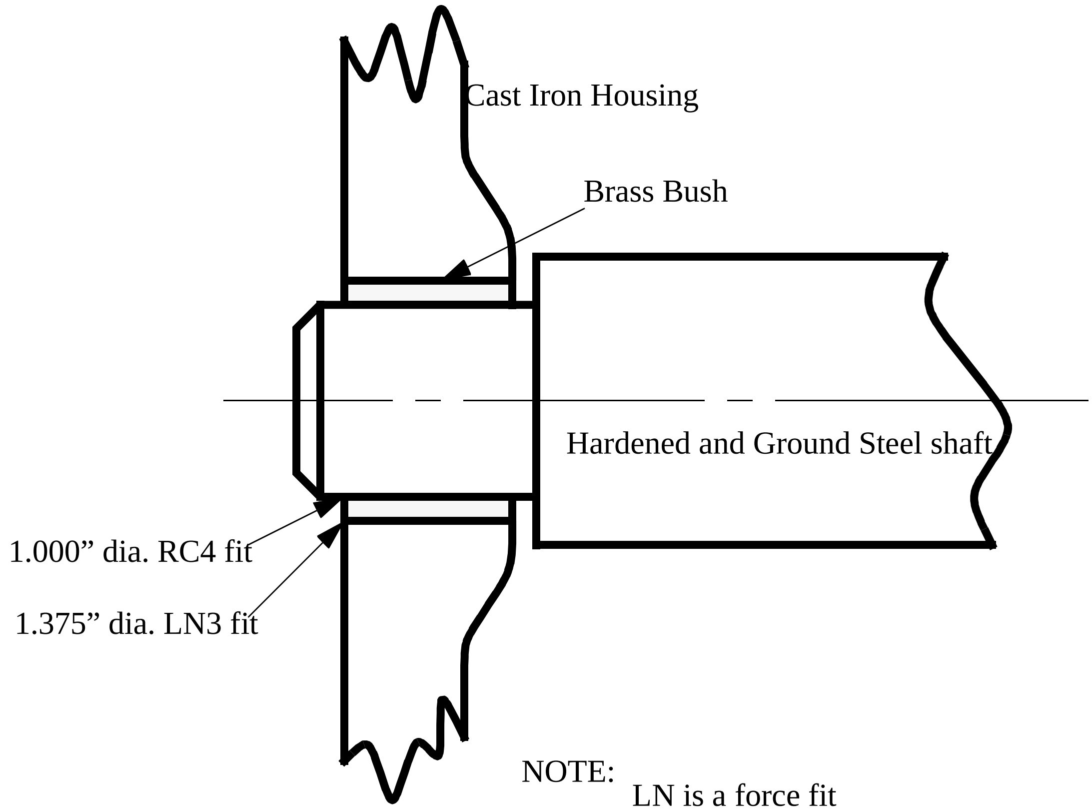
1. hole tolerance
2. allowance
3. shaft tolerance

From the tables for 2.25” dia. RC2 fit

Hole tolerance = +0.0007”
Allowance = 0.0004”
Shaft Tolerance = -0.0005”



• To go on further with a more complicated example, consider the hole shaft pair with a bushing

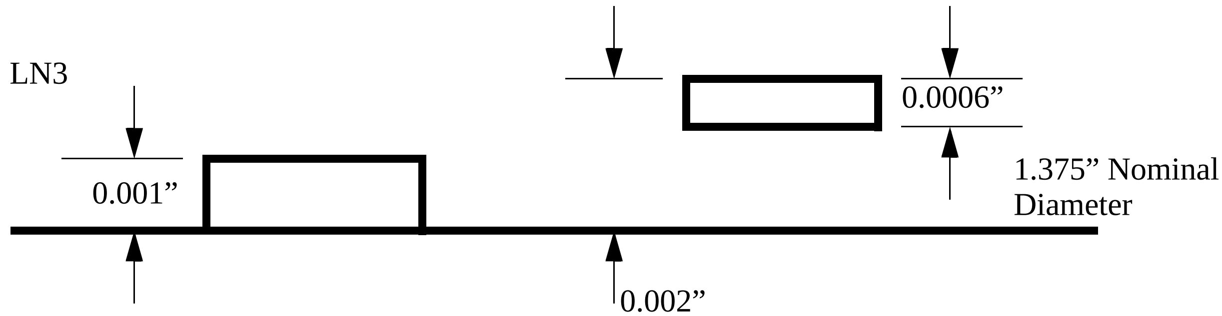


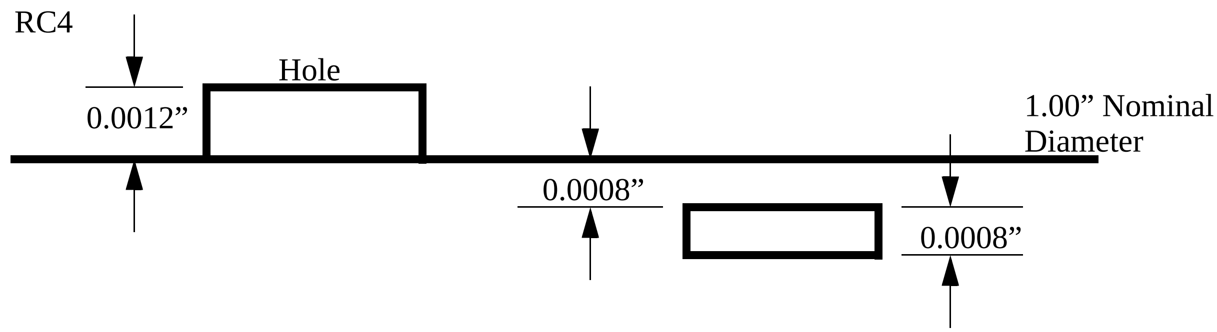
NOTE:

LN is a force fit
Class 3 is a heavy press fit

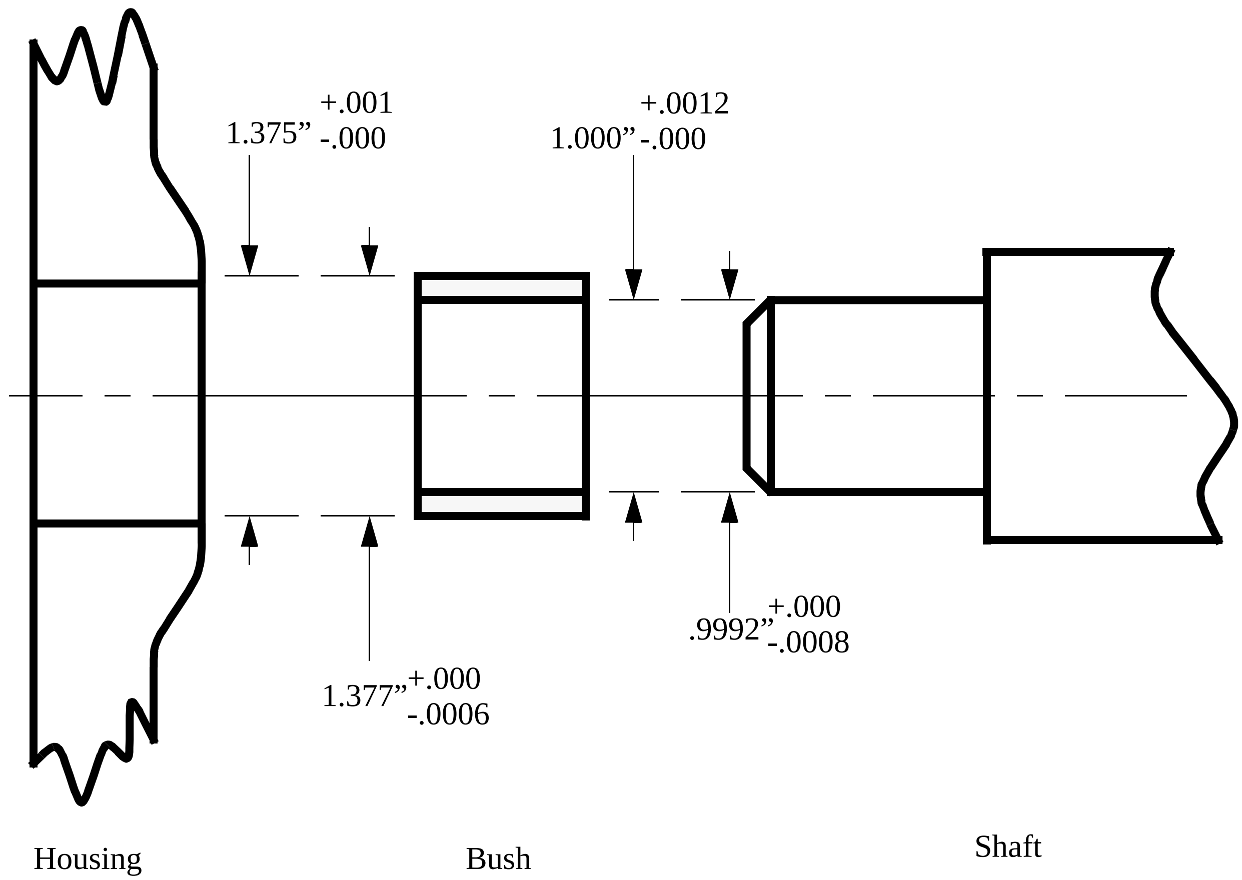
RC is a running clearance fit
Class 4 is a running fit
Lubricate with grease or oil

We want to detail and dimension the three parts, so first we draw the tolerance diagrams

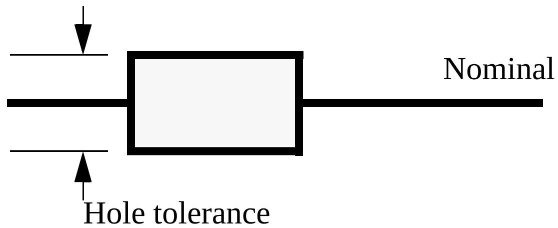




***NOTE: the values for the clearance are used differently when doing RC and LN fits



36.3 CSA MODIFIED FITS

CODE	MEANING
B	Bilateral Tolerance 
M	Matched fit - to permit enlarged tolerances for selective assembly
A	Arbitrary - adjustment of hole tolerance to facilitate rework

***NOTE: these symbols are not normally shown on shop drawings.

36.4 CSA LIMITS AND FITS

size range(in.)	Class RC1 Precision Sliding Fit (H5g4)			Class RC2 Sliding Fit (H6g5)			Class RC3 Precision Running Fit (H7f6)		
size range(in.)	hole tol. H5 (-0.0000)	minimum clearance	shaft tol. g4 (+0.0000)	hole tol. H6 (-0.0000)	minimum clearance	shaft tol. g5 (+0.0000)	hole tol. H7 (-0.0000)	minimum clearance	shaft tol. f6 (+0.0000)
0.0 - 0.12	+0.00015	0.0001	-0.00012	+0.00025	0.0001	-0.00015	+0.0004	0.0003	-0.00025
0.12 - 0.24	+0.0002	0.00015	-0.00015	+0.0003	0.00015	-0.0002	+0.0005	0.0004	-0.0003
0.24 - 0.40	+0.00025	0.0002	-0.00015	+0.0004	0.0002	-0.00025	+0.0006	0.0005	-0.0004
0.40 - 0.71	+0.0003	0.00025	-0.0002	+0.0004	0.00025	-0.0003	+0.0007	0.0006	-0.0004
0.71 - 1.19	+0.0004	0.0003	-0.00025	+0.0005	0.0003	-0.0004	+0.0008	0.0008	-0.0005
1.19 - 1.97	+0.0004	0.0004	-0.0003	+0.0006	0.0004	-0.0004	+0.0010	0.0010	-0.0006
1.97 - 3.15	+0.0005	0.0004	-0.0003	+0.0007	0.0004	-0.0005	+0.0012	0.0012	-0.0007
3.15 - 4.73	+0.0006	0.0005	-0.0004	+0.0009	0.0005	-0.0006	+0.0014	0.0014	-0.0009
4.73 - 7.09	+0.0007	0.0006	-0.0005	+0.0010	0.0006	-0.0007	+0.0016	0.0016	-0.0010
7.09 - 9.85	+0.0008	0.0006	-0.0006	+0.0012	0.0006	-0.0008	+0.0018	0.0020	-0.0012
9.85 - 12.41	+0.0009	0.0008	-0.0006	+0.0012	0.0008	-0.0009	+0.0020	0.0025	-0.0012
12.41 - 15.75	+0.0010	0.0010	-0.0007	+0.0014	0.0010	-0.0010	+0.0022	0.0030	-0.0014
15.75 - 19.69	+0.0010	0.0010	-0.0008	+0.0016	0.0012	-0.0010	+0.0025	0.0040	-0.0016
19.69 - 30.09				+0.0020	0.0016	-0.0012	+0.0030	0.0050	-0.0020
30.09 - 35.47				+0.0025	0.0020	-0.0016	+0.0040	0.0060	-0.0025
							hole H6		shaft f7
35.47 - 41.49							+0.0025	0.006	-0.004
41.49 - 56.19							+0.003	0.008	-0.005
56.19 - 76.39							+0.004	0.010	-0.006
76.39 - 100.9							+0.005	0.012	-0.008
100.9 - 131.9							+0.006	0.016	-0.010
131.9 - 171.9							+0.008	0.018	-0.012
171.9 - 200							+0.010	0.022	-0.016

size range(in.)	Class RC4 Close Running Fit (H8f7)			Class RC5 Medium Running Fit (H8e7)			Class RC6 Medium Running Fit (H9e8)		
size range(in.)	hole tol. H8 (-0.0000)	minimum clearance	shaft tol. f7 (+0.0000)	hole tol. H8 (-0.0000)	minimum clearance	shaft tol. e7 (+0.0000)	hole tol. H9 (-0.0000)	minimum clearance	shaft tol. e8 (+0.0000)
0.0 - 0.12	+0.0006	0.0003	-0.0004	+0.0006	0.0006	-0.0004	+0.0010	0.0006	-0.0006
0.12 - 0.24	+0.0007	0.0004	-0.0005	+0.0007	0.0008	-0.0005	+0.0012	0.0008	-0.0007
0.24 - 0.40	+0.0009	0.0005	-0.0006	+0.0009	0.0010	-0.0006	+0.0014	0.0010	-0.0009
0.40 - 0.71	+0.0010	0.0006	-0.0007	+0.0010	0.0012	-0.0007	+0.0016	0.0012	-0.0010
0.71 - 1.19	+0.0012	0.0008	-0.0008	+0.0012	0.0016	-0.0008	+0.0020	0.0016	-0.0012
1.19 - 1.97	+0.0016	0.0010	-0.0010	+0.0016	0.0020	-0.0010	+0.0025	0.0020	-0.0016
1.97 - 3.15	+0.0018	0.0012	-0.0012	+0.0018	0.0025	-0.0012	+0.0030	0.0025	-0.0018
3.15 - 4.73	+0.0022	0.0014	-0.0014	+0.0022	0.0030	-0.0014	+0.0035	0.0030	-0.0022
4.73 - 7.09	+0.0025	0.0016	-0.0016	+0.0025	0.0035	-0.0016	+0.0040	0.0035	-0.0025
7.09 - 9.85	+0.0028	0.0020	-0.0018	+0.0028	0.0040	-0.0018	+0.0045	0.0040	-0.0028
9.85 - 12.41	+0.0030	0.0025	-0.0020	+0.0030	0.0050	-0.0020	+0.0050	0.0050	-0.0030
12.41 - 15.75	+0.0035	0.0030	-0.0022	+0.0035	0.0060	-0.0022	+0.0060	0.0060	-0.0035
15.75 - 19.69	+0.0040	0.0040	-0.0025	+0.0040	0.0080	-0.0025	+0.006	0.008	-0.004
19.69 - 30.09	+0.005	0.005	-0.003	+0.005	0.010	-0.003	+0.008	0.010	-0.005
30.09 - 35.47	+0.006	0.006	-0.004	+0.006	0.012	-0.004	+0.010	0.012	-0.006
	hole H7		shaft f8	hole H7		shaft e8	hole H8		shaft e9
35.47 - 41.49	+0.004	0.006	-0.006	+0.004	0.012	-0.006	+0.006	0.012	-0.010
41.49 - 56.19	+0.005	0.008	-0.008	+0.005	0.016	-0.008	+0.008	0.016	-0.012
56.19 - 76.39	+0.006	0.010	-0.010	+0.006	0.020	-0.010	+0.010	0.020	-0.016
76.39 - 100.9	+0.008	0.012	-0.012	+0.008	0.025	-0.012	+0.012	0.025	-0.020
100.9 - 131.9	+0.010	0.016	-0.016	+0.010	0.030	-0.016	+0.016	0.030	-0.025
131.9 - 171.9	+0.012	0.018	-0.020	+0.012	0.035	-0.020	+0.020	0.035	-0.030
171.9 - 200	+0.016	0.022	-0.025	+0.016	0.045	-0.025	+0.025	0.045	-0.040

size range(in.)	Class RC7 Free Running Fit (H9d8)			Class RC8 Loose Running Fit (H10c9)			Class RC9 Loose Running Fit (H9b10)		
size range(in.)	hole tol. H9 (-0.0000)	minimum clearance	shaft tol. d9 (+0.0000)	hole tol. H10 (-0.0000)	minimum clearance	shaft tol. c9 (+0.0000)	hole tol. H9 (-0.0000)	minimum clearance	shaft tol. b1- (+0.0000)
0.0 - 0.12	+0.0010	0.0010	-0.0006	+0.0016	0.0025	-0.0010	-0.0010	0.0040	-0.0016
0.12 - 0.24	+0.0012	0.0012	-0.0007	+0.0018	0.0028	-0.0012	-0.0012	0.0045	-0.0018
0.24 - 0.40	+0.0014	0.0016	-0.0009	+0.0022	0.0030	-0.0014	-0.0014	0.0050	-0.0022
0.40 - 0.71	+0.0016	0.0020	-0.0010	+0.0028	0.0035	-0.0016	-0.0016	0.0060	-0.0028
0.71 - 1.19	+0.0020	0.0025	-0.0012	+0.0035	0.0045	-0.0020	-0.0020	0.0070	-0.0035
1.19 - 1.97	+0.0025	0.0030	-0.0016	+0.0040	0.0050	-0.0025	-0.0025	0.0080	-0.0040
1.97 - 3.15	+0.0030	0.0040	-0.0018	+0.0045	0.0060	-0.0030	-0.0030	0.0090	-0.0045
3.15 - 4.73	+0.0035	0.0050	-0.0022	+0.0050	0.0070	-0.0035	-0.0035	0.010	-0.005
4.73 - 7.09	+0.0040	0.0060	-0.0025	+0.0060	0.0080	-0.0040	-0.0040	0.012	-0.005
7.09 - 9.85	+0.0045	0.0070	-0.0028	+0.0070	0.0100	-0.0045	-0.0045	0.015	-0.007
9.85 - 12.41	+0.0050	0.0080	-0.0030	+0.008	0.012	-0.005	-0.005	0.018	-0.008
12.41 - 15.75	+0.0060	0.010	-0.0035	+0.009	0.014	-0.006	-0.006	0.022	-0.009
15.75 - 19.69	+0.006	0.012	-0.004	+0.010	0.016	-0.006	-0.006	0.025	-0.010
19.69 - 30.09	+0.008	0.016	-0.005	+0.012	0.020	-0.008	-0.008	0.030	-0.012
30.09 - 35.47	+0.0010	0.020	-0.006	+0.016	0.025	-0.010	-0.010	0.040	-0.016
	Hole H8		shaft c9	Hole H10		shaft c10	Hole H10		b10
35.47 - 41.49	+0.006	0.020	-0.010	+0.010	0.025	-0.016	-0.016	0.040	-0.025
41.49 - 56.19	+0.008	0.025	-0.012	+0.012	0.030	-0.020	-0.020	0.050	-0.030
56.19 - 76.39	+0.010	0.030	-0.016	+0.016	0.040	-0.025	-0.025	0.060	-0.040
76.39 - 100.9	+0.012	0.040	-0.020	+0.020	0.050	-0.030	-0.030	0.080	-0.050
100.9 - 131.9	+0.016	0.050	-0.025	+0.025	0.060	-0.040	-0.040	0.100	-0.060
131.9 - 171.9	+0.020	0.060	-0.030	+0.030	0.080	-0.050	-0.050	0.130	-0.080
171.9 - 200	+0.025	0.080	-0.040	+0.040	0.100	-0.060	-0.060	0.150	-0.100

36.5 THE I.S.O. SYSTEM

• Basic features of this system were,
  - several diameter steps
  - 22 holes and 22 shafts
  - 16 tolerance grades

36.6 PRACTICE PROBLEMS

1. On a ferris wheel we have a 3.5” running journal that is to be pressure lubricated. The fit

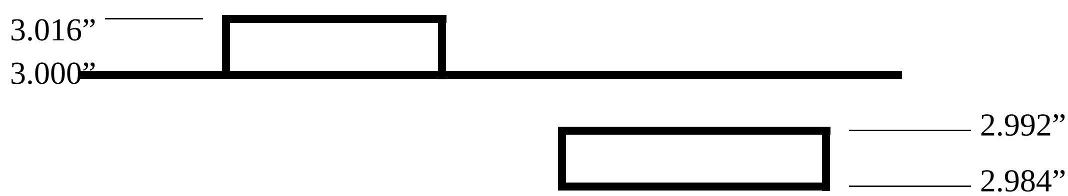
selected for this application is RC4. Use a tolerance diagram to determine the tolerances required on a final drawing. Sketch the hole, and shaft using appropriate drafting techniques.

2. Do complete drawings for a 3.000” hole shaft pair if they have a RC3 fit.

37. Clearance fits are found in,
   a) fitted assembly.
   b) interchangeable assembly.
   c) selective assembly.
   d) all of the above.

38. Which statement is more true?
   a) production errors cause tolerances.
   b) there are no standard tolerances.
   c) both a) and b) are completely true.
   d) neither a) or b) is true.

39. Given the diagram below, what will the average interference/clearance be?
   a) 0.008”
   b) 0.020”
   c) 0.032”
   d) none of the above



40. Briefly describe the relationship between tolerance and accuracy. (2%)

41. A hole shaft pair uses a bushing. We know that the fit between the shaft and bushing is LC5, with a nominal diameter of 7” and the fit between the bushing and outer hole is 8” with an FN3 fit. (8%)
   a) Draw the tolerance diagrams.
   b) Draw the final parts with dimensions and tolerances.
   c) What will the gap between the shaft and the bushing be?

42. WELDING/SOLDERING/BRAZING

• Welding is the process of joining two or more objects together. In general this is done by melting the adjacent surfaces, or by melting a third material that acts as a ‘glue’

• We can categorize welding by processes,

Arc	Carbon Electrode	Shielded	Shielded	
			Inert Gas	
		UnShielded	Carbon Arc	
			Twin Carbon Arc	
	Metal Electrode	Shielded	CO_2 Mig	CO_2
				Flux
				Arc-Spot
			Coated Electrode	
			Electro Slag	
			Imp. Tape	
			Inert Gas	Mig
				Tig
				Arc-Spot
			Plasma	
			Stud	
			Submerged	
		Unshielded	Bare Electrode	
			Stud	
Brazing	Block			
	Dip			
	Flow			
	Furnace			
	Induction			
	Resistance			
	Torch			
	Twin Carbon Arc			
Electron Beam				
Explosive				
Flow				
Forge	Die			
	Friction			
	Hammer			
	Roll			
Gas	Air Acetylene			
	Oxy Acetelene			
	Oxy Hydrogen			
	Pressure			
Induction				
Ion Beam				
Laser Beam				
Resistance	Flash			
	Percussion			
	Projection			
	Spot			
	Seam			
	Upset			
Thermit	Nonpressure			
	Pressure			
Ultrasonic				

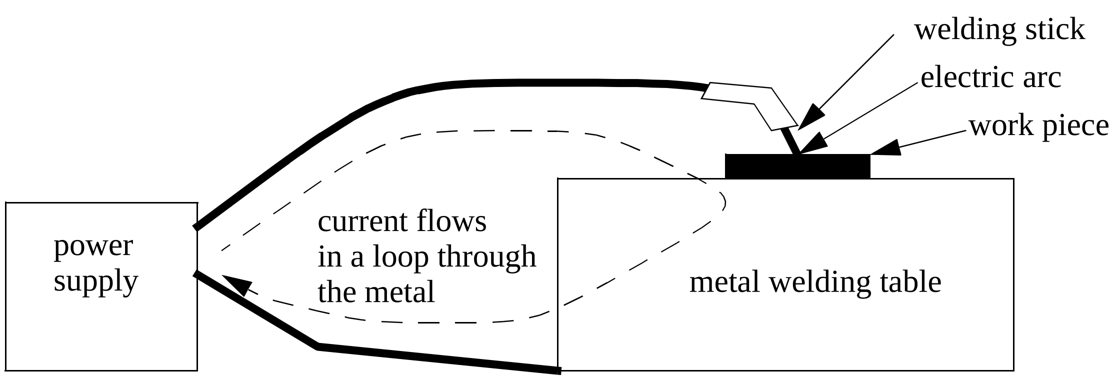
42.1 ADHESIVE BONDING

42.2 ARC WELDING

• Basically, an electric arc is used to heat base metals and a consumable filler rod.

• This is the most common form of welding and is used in about half of all applications.

• A power supply is used to create a high potential between an electrode (guided by the welder) and a metal work piece. When moved close enough electrodes break down the air and start to flow. The local current of the flow is so high that it heats metals up to 30000C or 54000F.



• Material is added during this welding process.This material can come from a consumable electrode, or from a rod of material that is fed separately.

• The electrodes/rods are often coated. This coating serves a number of functions,
- it protects the welder from contact
- it deoxidizes and provides a gas shield

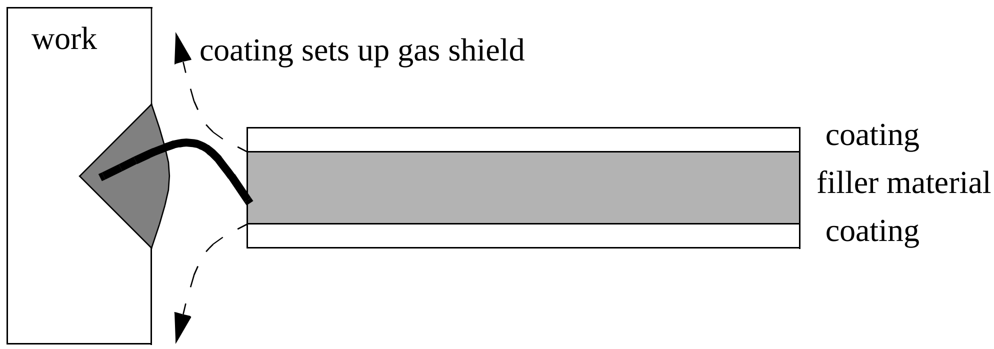
• Problems that arise in this form of welding is contamination of the metal with elements in the atmosphere (O, H, N, etc.). There can also be problems with surfaces that are not clean. Solutions to this include,

Gas shields - an inert gas is blown into the weld zone to drive away other atmospheric gases.

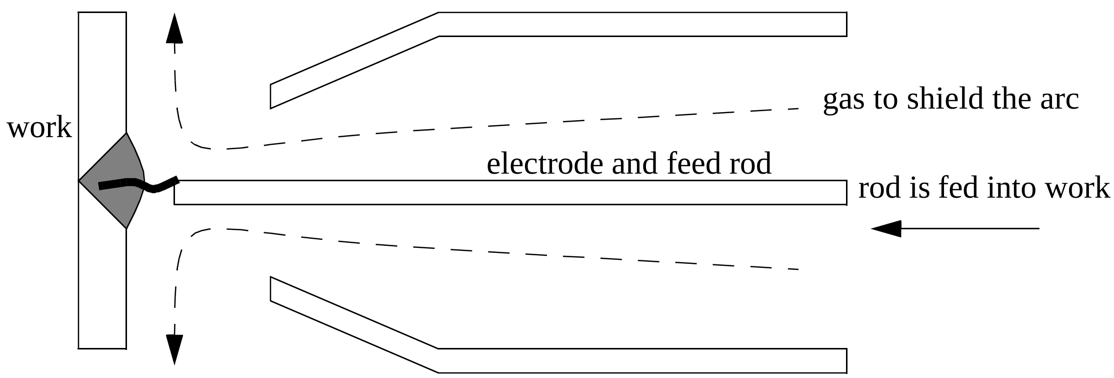
Flux - a material that is added to clean the surface, this may also give off a gas to drive away unwanted gases.

• Common types of processes include,

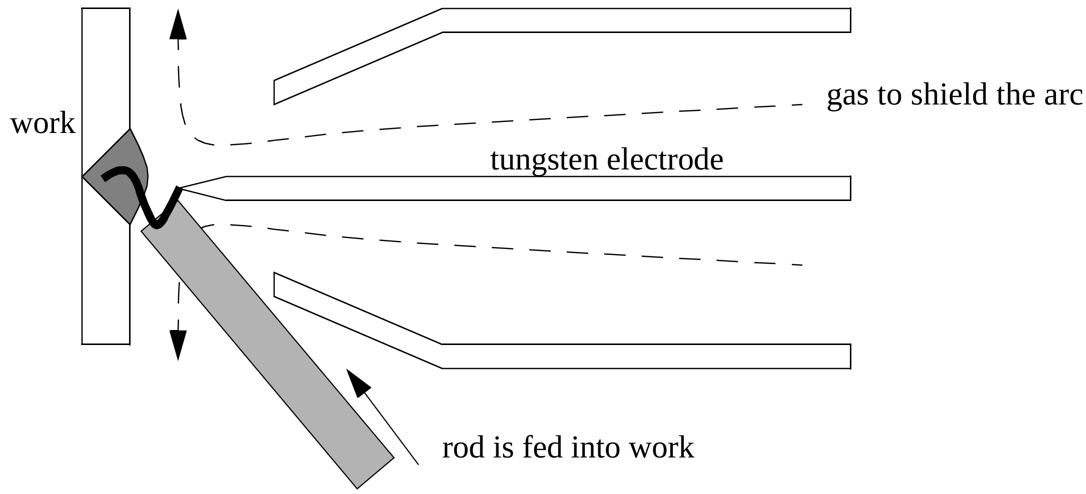
SMAW (Shielded Metal Arc Welding)/Stick Welding - A consumable electrode with a coating that will act as a flux to clean the metal, and to create a gas shield.



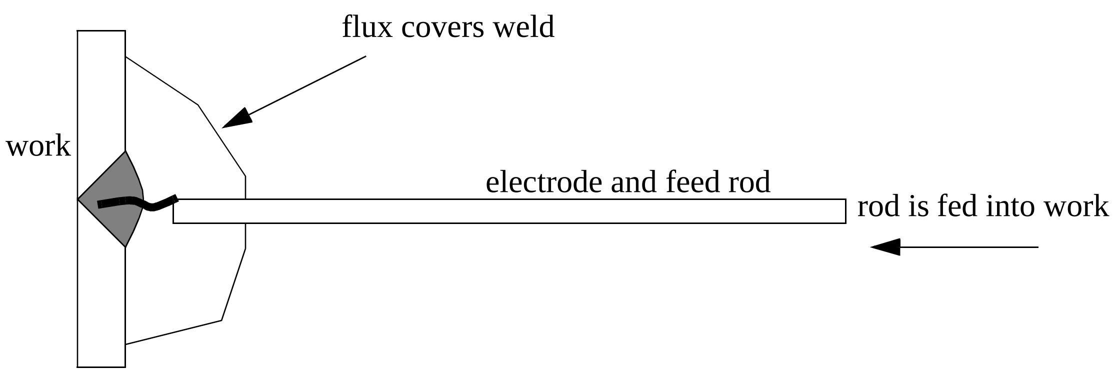
MIG (Metal Inert Gas) - A consumable electrode in a gas shield. In addition to simple materials, this can handle aluminum, magnesium, titanium, stainless steel, copper, etc. This torch is normally water or air cooled.



TIG (Tungsten Inert Gas) - A nonconsumable tungsten electrode is used with a filler rods and a gas shield. This can handle aluminum, titanium, stainless steel, copper, etc. This torch is normally water or air cooled.



SAW (Submerged Arc Welding) - A normal wire is used as a consumable electrode, and the flux is applied generously around the weld. The weld occurs within the flux, and is protected from the air.



• Process variables include,
- electrode current 50-300A is common
- voltage
- polarity
- arc length
- speed
- materials
- flux
- workpiece thickness

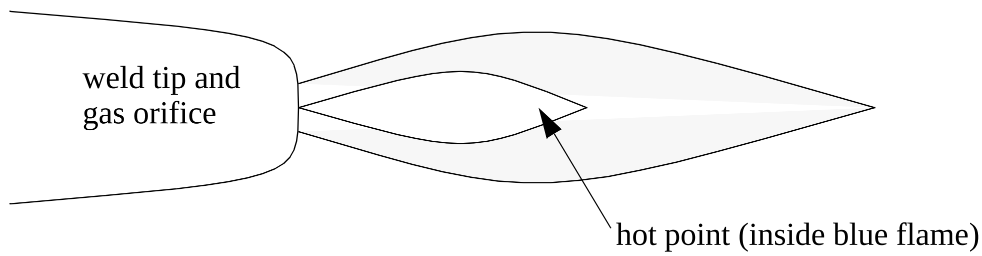
42.3 GAS WELDING

• Basically, filler and base materials are heated to the point of melting by a burning a gas.

• Two common types are,
  - oxygen-acetylene
  - mapp gas

• These are suited to a few applications, but they produce by-products that can contaminate the final weld.

• Typically the flame is adjusted to give a clean burn, and this is applied to the point of the weld.



• A welding rod will be fed in separately to melt and join the weld line.

• Flux can be used to clean the welds.

• Process variables include,
  - gas and oxygen flow rates
  - distance from surface
  - speed
  - material types
  - surface preparation of materials

42.4 SOLDERING AND BRAZING

• Basically, soldering and brazing involve melting a filler material that will flow into a narrow gap and solidify. It is distinct because the base materials should not be melted.

• The main difference is,
  - Soldering is done at a lower temperature, either with a propane torch, or an electric heater. It is intended for bonds with less required strength, such as electrical and plumbing applications.
  - Brazing is done at higher temperatures with oxyacetylene or mapp gas torches. These bonds tend to be higher and can be used for mechanical strength.

• General process considerations include,

- Suitable for gaps from 0.001” to 0.01”
- Surfaces must be sanded and cleaned before these processes are used.
- Flux is often used to deoxidize a surface so that the filler will adhere better. Typical fluxes include,
    - Brazing flux - fused borax or alcohol and borax paste
    - Soldering flux - inorganic salts (zinc ammonium chloride), muriatic acid, resin based
- Some fluxes are corrosive and should be removed after use.

• Materials include,
- Solder is often an alloy combination of two of tin, lead, silver, zinc, antimony or bismuth.
- Brazing metals are typically alloys such as,
    - brazing brass (60% Cu, 40%Zn)
    - manganese bronze
    - nickel silver
    - copper silicon
    - silver alloys (with/without phosphorous)
    - copper phosphorous

42.5 TITANIUM WELDING

• Titanium as a metal
- above 885°C the material undergoes beta phase transition to body centered cubic arrangements
- melts at 1800°C
- resistance to corrosion
- high affinity for carbon
- soft and ductile when annealed

• Above 260°C titanium absorbs oxygen, nitrogen, and hydrogen. This causes when welding, because in excess they make titanium brittle.

• Titanium welding requires,
- a very clean environment with no contaminants or other materials.
- no drafts
- the correct welding equipment

• To eliminate unwanted gases and moisture from being absorbed, a gas shield is used on both sides of the weld.

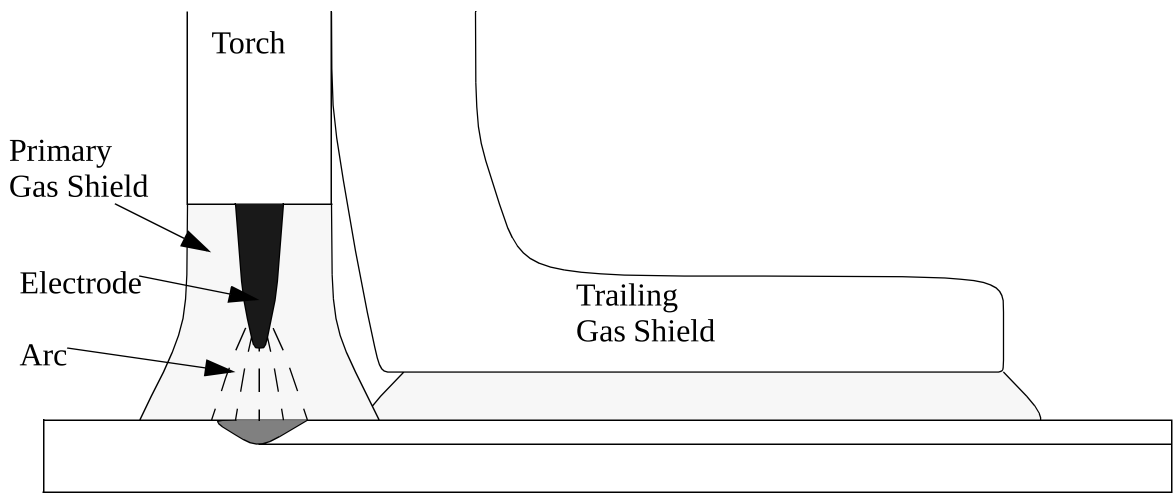
• The weld must be shielded until the temperature drops below 427°C.

• Gas tungsten arc welding,
  - gas is used to cover the tip of the torch, electrode and workpiece.

• The torch is,
  - a split copper collect holding a tungsten electrode. A nut tightens the collet and holds the electrode. The collet also serves to conduct current to the electrode.
  - tubes delivers gas to the torch, and it is channeled to the electrode in such a way as to ensure uniform coverage.

• Gas cups are,
  - Ceramic, metals or high temperature glass is used to direct the gas about the electrode. The size typically effects the gas consumption.

• An optional trailing shield focuses gas on the now welded joint, to allow proper cooling time.



• The electrode stickout (or electrode extension) is the distance that the electrode protrudes out the end of the collet. A larger stickout is proportional to the energy delivered, and the size of the gascap, and it allows better visibility of the work.

• A gas lens can be used to focus/balance the flow of gases, it can be used without a gas cup, or with one to improve gas coverage.

• Gas backups are placed on the back of the weld seam, purging is used when the back of the weld is enclosed (eg tubes).

• Typical welding parameters,

Sheet Thickness (in.)	Filling Wire dia. (in.)	Filling Wire feed (ipm)	Gas	Arc Voltage (V)	Welding Current (A)	Travel Speed (ipm)
0.008	NA		He	14	10	16
0.030	NA		Ar	10	25-30	10
0.060	NA		Ar	10	90-100	10
0.060	0.062	22	Ar	10	120-130	12
0.090	NA		Ar	12	190-200	10
0.090	0.062	22	Ar	12	200-210	12
0.125	0.062	20	Ar	12	220-230	10

• Joints can be prepared by machining. If torch cutting has been used, the edges must be ground to remove the by-products of the cutting torch (typically > 1/16”). After grinding, burrs should be filed off.

• Surface cleaning should include,
1. degassing
2. brushing with stainless steel
3. sandblast off heavy scale

• Welding can also be done is a sealed chamber flooded with an inert gas. The chamber can have gas evacuated, and then reflooded, or gas flow will eventually exchange air for gas.

42.5.1 Practice Problems

1. TRUE / FALSE - Oxygen is used to enhance oxidation when welding titanium.

42.6 PLASTIC WELDING

• Well suited to joining of thermoplastics.

• Types of plastics used in welding are,

Material	Welding Temp. (°C)
ABS	350
Acylics	350
PC	350
Polyamide	400
Polybutylene	350
Polyethylene high density	300
Polyethylene low density	270
Polypropylene	300
Polypropylene rubber	300
Polyurethane	300-350
PVC high density	300
PVC low density	400-500

• Plastics to be joined should be compatible. A common method is based on trial and error testing.

• To determine plastic types burning small samples with a low flame gives the following observations,

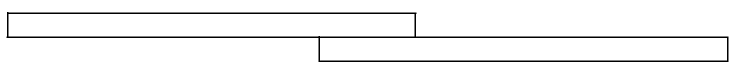
Material	Observations
ABS	smells sweet, black sooty flame, does not extinguish
Polyamide	smells like burnt horn, stringy, does not extinguish
Polycarbonate	black sooty smoke, may extinguish
Polyethylene	smells bad, feels like wax, burns like wax, drips
Polypropylene	smells like wax, feels like wax, burns like wax, drips
PVC	acrid smell, black smoke, does not extinguish

• Welding of thermoplastics involves heating, contact, cooling and bonding.

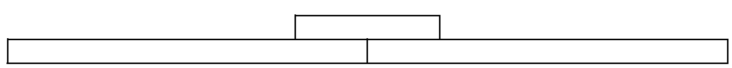
• Joints may be weakened by incomplete fusion, oxidation or thermal degradation of the plastic.

• Melting may be done by,
  - gas or electric gun
  - heated tool
  - induction heating
  - friction
  - spinning

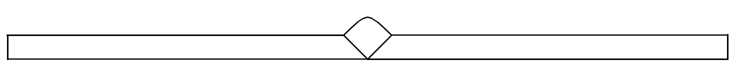
• Sheet welding,
- heat and pressure are applied at an overlapped joint between thin sheets.
- rollers join the sheets (one roller is often motor driven and heated while the other just applies pressure).
- typical variables are,
    - roller temperatures
    - feed rate
    - pressure
- underheating leads to a loose seam.
- overheating leads to a hole formation.
- parametric setting is very sensitive.
- welds can be done on tables with a hand roller and a heat gun.
- advantages
    - simple tools
- disadvantages
    - hard to set parameters
- preparation of welded sheets.



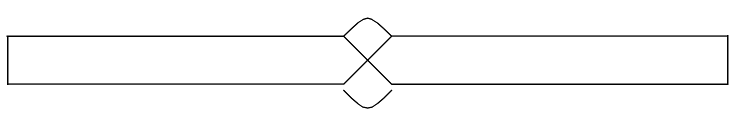
Overlap - less than 3 mm



Butt with lap



Single butt



Double butt

    - if welded plastics to repair cracks, drill holes at the ends to stop crack propagation.

• Hot air/gas welding,
- Used successfully with molded parts in,
    - PVC
    - polyvinylidene chloride
    - polyethylene

- acrylic
- polychlorotriflourethylene
- Operation steps,
  1. pieces positioned but a gap of 1/16” left
  2. a suitable welding (often same material) rod is pushed into the gap
  3. a hot blast often 400-600°F is directed at the tip of the welding rod and surfaces to be welded. * if a torch to focus distance of 1-2” is used, a drop in temperature of 200°F will occur, the resulting temperature should be the melting temperature of the plastic.
- The final strength ranges from 50% maximum for high density materials, to near 100% for low densities.
- The heating guns are similar to common hair dryers with heaters and fans, and vents to control air flow rates.
- The heat calls for safety measures.
- Nozzles - a variety of nozzles and tools are available.
- Advantages,
  - simple tools
- Disadvantages,
  - welding angles hard to set

• Tack welding,
- parts are put in position.
- the gun temperature is allowed to heat up (a tack welding nozzle is used).
- the gun is put at an angle of 30-40°F to the weld and held in place until melting begins.
- the gun is slowly drawn along the seam.
- since the tack weld is weak (used for positioning) subsequent welding is required.

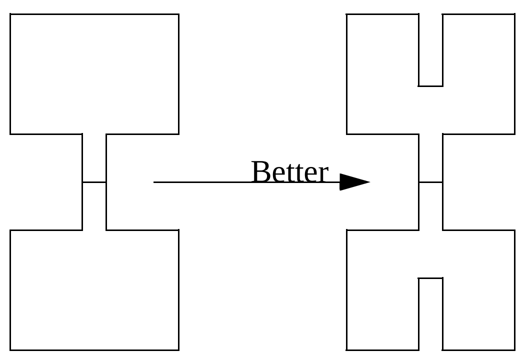
• General welding,
- operation
  1. the gun is held 90° to the weld and a rod is inserted.
  2. once the rod starts to melt, the gun is turned to a 45° angle and moved steadily along the weld.
  3. The gun is moved in an elliptical path over the weld with an amplitude of about 1”.
  4. The rod is forced into the groove with a pressure of about 3-6 lbs. This pressure prevents air from entering the weld. An angle of 45° to 90° is used for the rod.
  5. When ending a weld, the heat is turned off, and after cooling the rod is twisted off, or for continuous welds there should be an overlap of 1/2”.
  6. If required a weld can be restarted by cutting the previous weld at an angle, and starting from that point.

• Speed Welding
- the rod and gas are fed side by side.
- the rod is heated in the gun, and is “wiped” out as it leaves the gun.
- when starting pressure is applied to the rod and a sharpened tip is forced into the work.

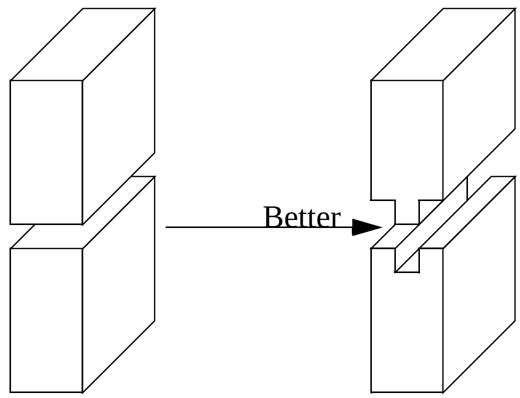
- as the rod starts to melt, the gun is lowered to 45° and drawn along. The welding rod is pulled in itself.
- moving the tip too fast will result in beading and too slow will result in charring.
- the weld is stopped by standing the gun at 90° to the surface and pulling the gun off. The rod is then cut off.

• Tractor Welding (Machine Welding),
- a hot air gun and rollers are driven over a surface by motors.
- a tape can be dispensed that will join the sheets or the two sheets can be overlapped.
- advantages,
    - fully automated
    - easy to set parameters
- disadvantages,
    - special equipment required

• Ultra Sonic Welding,
- basically a high frequency vibration is directed through a plastic joint. The vibration causes friction, and then heat, often causing a solid bond in less than a second.
- frequencies above 20 KHz.
- the distance the vibration travels has a great deal to do with determining the classification.
- very well suited to rigid thermo plastic parts.
- good designs make direct application of the vibrations possible.



- a smaller contact area increases the energy concentration. As a result V-notches, tongues, pins, and other special joints are commonly used.



- if remote sealing is necessary, thicker walls should be incorporated into the part design
- epoxy molds can be used to reinforce weaker parts when doing this operation.
- advantages,
    - fast
    - clean
    - no extra materials needed
- disadvantages,
    - tool design required
    - simple design rules not always available

• Linear Vibration Welding,
- similar to Ultrasonic Welding, except that frequencies are about one hundred Hz and amplitude are mm.
- this is best used with high coefficient of friction, low viscosity plastics.

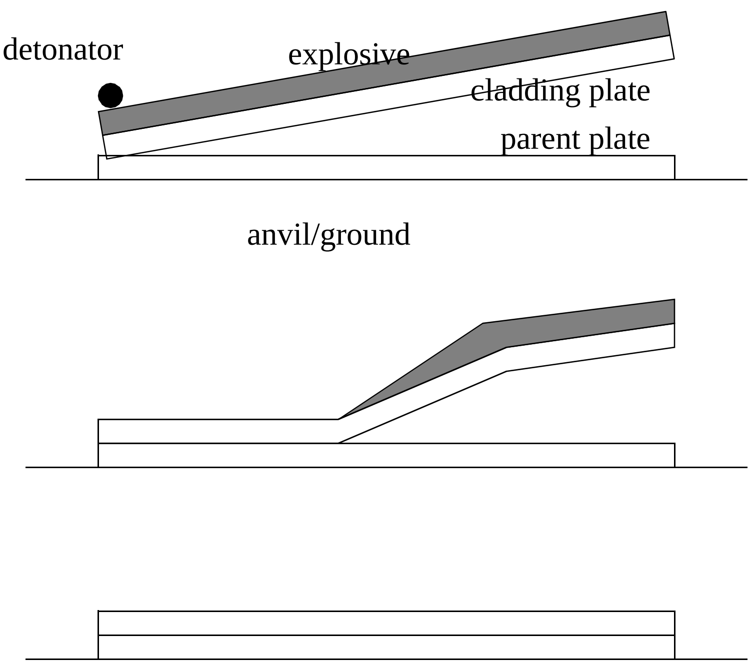
• Spin/Friction Welding,
- two parts are spun and the contact area builds up heat through friction and pressure. The pressure forces a good bond between parts and drives out bobbles.
- flashing may occur with this method.
- advantages,
    - produces a good weld
    - air does not enter during welding
    - inexpensive machines, such as drill presses may be used
- disadvantages,
    - circular weld joints are required

• Testing Plastic Welds,
- a handheld gun can be used to generate arcs. The sparks are generated with voltages up to 55 KV at 200 KHz.
- operation,
    1. The gun is calibrated to spark at distances just over the weld thickness (to a ground plate).
    2. the ground plate is placed behind the weld.

3. as the probe is moved over the weld, sparks will jump when a gap in the weld moves between the probe and the ground plate.

42.7 EXPLOSIVE WELDING

• The basic mechanism is based on molecular bonding, as a result of high velocity impact. The high velocities are promoted by carefully detonated explosives.



• The process is done at room temperature in air, water or vacuum.

• Surface contaminants tend to be blown off the surface.

• Typical impact pressures are millions of psi.

• The process can be done in vacuum to reduce sound and blast.

• Well suited to metals that are prone to brittle joints when heat welded, such as,
  - aluminum on steel
  - titanium on steel

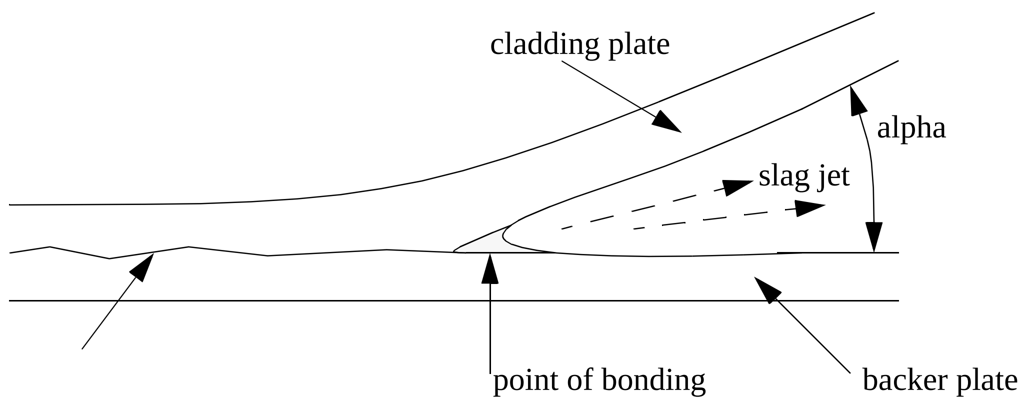
• The process does not work well for,
  - brittle metals with <5% tensile elongation
  - Charpy V-notch value < 10 ft.lb.

• If two materials can be brought close enough together, they will bond at a molecular level.

• This normally does not happen because surface contaminants (ie oxides, nitrides and absorbed gases) prevent a close approach of surfaces.

• Normal welding overcomes this problem by melting materials so that they mix in liquid phases.

• Important factors are,
  - critical velocity
  - critical angle



• When parameters match up, the surfaces form a liquid jet starting at the point they impact, and is directed away from the welded seam.

• The plates have an airgap between, and plastic, liquid or granular explosives are placed on the plate. The backer plate is rested on an anvil (eg sand could be used for lighter backers, or concrete/steel for stronger backers).

• The cladding plate can be supported with tack welded supports at the edges, or the metal inserts.

• Two plate shapes with straight constant interface or angled interface clearance.

• High velocity explosives require smaller gaps between plates, and buffers such as rubber and plexiglas. Angled interfaces are only used for high velocity explosives.

• Typically the detonation velocity should not exceed 120% of the sonic velocity in the metal.

• Typical explosive forms are,
  - plastic flexible sheet
  - cord
  - pressed shapes
  - cast shapes
  - powder/granular

- There is a maximum velocity for welding, above this the thermal effects weaken the joint.

- To efficiently use explosives the plate separation is 1/2 to 1 times the cladding plate thickness.

- High velocity explosives, 15-25,000 ft/sec. (4572-7620 m/s),
    - TNT
    - RDX
    - PETN
    - Composition B
    - Composition C4
    - Detasheet
    - Primacord

- Medium velocity explosives, 5-15,000 ft/sec. (1524-4572 m/s),
    - Ammonium nitrate
    - Ammonium perchlorate
    - Amatol
    - Nitroguonidine
    - Dynamites
    - diluted PETN

- 3 bond types,
    - straight, direct metal-to-metal - best type of bonding but difficult to obtain when collision velocity less than critical velocity.
    - wavy - the interface is strong and the interface has waves.
    - straight, but with a continuous layer - a weaker bond that results when the collision velocity is too high and the alloy bonds are strong.

- Advantages,
    - can bond many dissimilar, normally unweldable metals
    - the lack of heating preserves metal treatment
    - the process is compact, portable, and easy to contain
    - inexpensive
    - welds can be done from in2 to hundreds of ft2
    - no need for surface preparation
    - the backer plate has no size limits

- Disadvantages,
    - the metals must have high enough impact resistance, and ductility.
    - the geometries welded must be simple - flat, cylindrical, conical.
    - the cladding plate cannot be too large.
    - noise and blast can require worker protection, vacuum chambers, buried in sand/water.

- Typical applications,
    - spot welding

- reinforcing aerospace materials with dissimilar metal ribs
- seam and lap welds.
- tubular transition joints
- flat plates

42.7.1 Practice Problems

1. TRUE / FALSE - Ductile metals can be welded with explosives.

2.What is the purpose of flux in welding?

3. List 20 parts you have seen that are welded. Indicate which welding process is the most appropriate for each.

4. What types of processes would be best suited for joining the following items? Indicate why.
a) two 12” dia. plastic pipes.
b) two 12” dia. steel pipes.
c) the sides of a plastic bag for potato chips.
d) two aluminum plates along one edge.
e) an aluminum and steel plate into a laminated plate.
f) steel muffler pipes.

5. What are the primary differences between welding soldering and gluing?

43. AESTHETIC FINISHING

• There are a number of operations which have very little impact on the engineering aspects of a product operation, but are important to the final user. These include,
  - color
  - markings and labels

43.1 CLEANING AND DEGREASING

• Various methods remove contaminants
  - Chemical degreasing - removes chemicals and prepares surfaces
  - Solvent degreasing - contaminants dissolve in a solvent bath
  - Vapor degreasing - the solvents are sprayed or vaporized to dissolve contaminants
  - Ultrasonic cleaning - a cleaning solution is used with ultrasonic vibrations

43.2 PAINTING

43.2.1 Powder Coating

• Basically a power is distributed over the surface of a part. Subsequent heat then melts the plastic to leave behind a high quality surface.

• Advantages,
  - energy and labor cost reductions
  - high efficiency
  - environmentally safe
  - good quality finish

• In contrast, paint uses solvents that dissolve whereas powder coatings are applied and then heat cured.

• The basic steps are,
  1. apply a finely ground powder coating to a part.
  2. Heat the part to melt and fuse the powder.

• The parts can be coated with a fluidized bed. The hot part is dipped in a fluidized vat of powder where it coats and hardens. A part curing process is also done.

• Parts can also be coated with electrostatically charged powder that is oven cured.

• Thermoplastic powders are commonly used.
  - They melt and reset at elevated temperatures, but do not change chemically
  - The molecular weight is high.
  - The materials are hard to grind into fine powders.
  - The thermoplastic coatings tend to be thicker (0.008” to 0.04”)and applied by the fluidized bed method.
  - Typical materials are,
    - polyethylene
    - polypropylene
    - nylon
    - polyvinyl chloride
    - thermoplastic polyester
  - primers can be used

• Thermosets are another common material,
  - in uncured state the components are low molecular weight solid resins. When heated the resins chemically bond to longer molecular chains.
  - typical coating thicknesses are 0.001” to 0.003”
  - typical materials are,
    - epoxy
    - hybrids
    - acrylic
    - TGIC polyester
    - urethane polyester
  - applied by a spray gun

• Pigments can be added to modify basic colors.

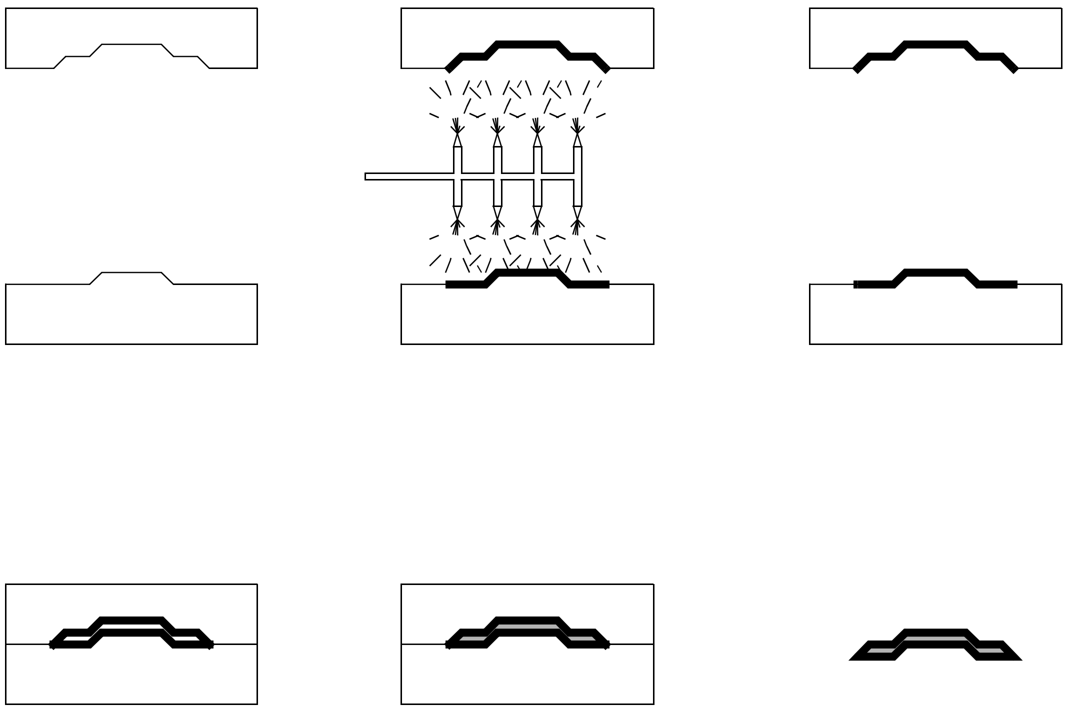
• Additives can be used for other properties,
  - hardness
  - salt spray resistance
  - strength
  - impact resistance
  - stain resistance

• Mechanical Surface Preparation,
  - the surface is mechanically worked to remove unwanted coatings, and roughen the surface to help the coating stick.
  - typical methods are,
    - airblasting with sand or slag abrasives in open or closed environment.
    - centrifugal wheel blasting.

• Chemical surface preparation,

- often used on galvanized steel, steel and aluminum
- typical cleaners include,
  - alkalines
  - acids
  - neutral
  - solvents
  - emulsions

• In mold powder coating,
  - powders are sprayed into mold cavities before the part is molded.
  - before/after/during molding the cavity is heated to 280-350°F and the coating chemically bonds to the part making better adhesion.
  - advantages of this method are,
    - chip and impact resistance
    - conductive primers can be applied with this method to permit electrostatic coatings.
    - other painting facilities can be eliminated
    - shelf lives for materials is over a year
    - good coverage, including complex geometries, uniform thickness.
  - The basic process is,
    1. the mold is opened
    2. spray guns (electrostatic) are moved into the mold and spray powder in to coat the empty mold
    3. the powder cures on the surface that has been preheated to 280-350°F
  - A typical cycle time, including the coating, is less than half a minute
  - This technique is most often used with thermoset compression molding.



- typical applications include,
    - autobody panels
    - sanitary fixtures
    - sports equipment
    - bathroom fixtures
    - machine and electrical housings
- multiple molds can be coated at once
- robotic coaters are available
- limitations,
    - plastics can be hard to direct into the mold
    - parting lines of the mold build up extra material
    - the powder between the mold halves must be removed after the mold halves are brought together.

• Booths can be used to recover powder that is sprayed but does not adhere to the part.
- gravity assisted booth
- belt booths
- self contained booth

• Systems can be used to remove most of the unbonded particles from the air. The extra components include,
- ducts
- a cyclone precipitator
- filters

• Belt Booths -The booths have many of the components of a normal booth, except that the unbonded powder is drawn onto a conveyor belt - the circulating air is drawn though the belt, but the powder is filtered out.

• Self contained booth - an all in one unit that allows fast changeovers for new colors.

• Two types of ovens used,
  - convective ovens
  - infrared ovens

• Advantages,
  - no incinerators or air scrubbers (no exhaust)
  - no toxic by-products

- better properties than paint
- fast cure times

• Disadvantages,
- limited colors
- color changeovers limited
- oven curing required
- some materials damaged by UV
- deep recesses not well covered

43.3 COATINGS

• A coating can be applied to protect surfaces and/or improves appearances.

• Processes include,

Chrome plating - a reaction with chromic acid leaves a chrome plating on a part
Phosphate plating - a reaction with phosphoric acid leaves a phosphoric coating on a part
Electroplating - thin metal coatings are made by dissolving an anode in an electrolytic solution with an electric current
Hot dip coating - parts are dipped in molten metal and get a new coating
Vacuum deposition (ion plating) - metals are vaporized in a vacuum chamber and these deposit in thin layers on a surface

43.4 MARKING

43.4.1 Laser Marking

• General problems with other methods are,
- mark permanence
- poor quality

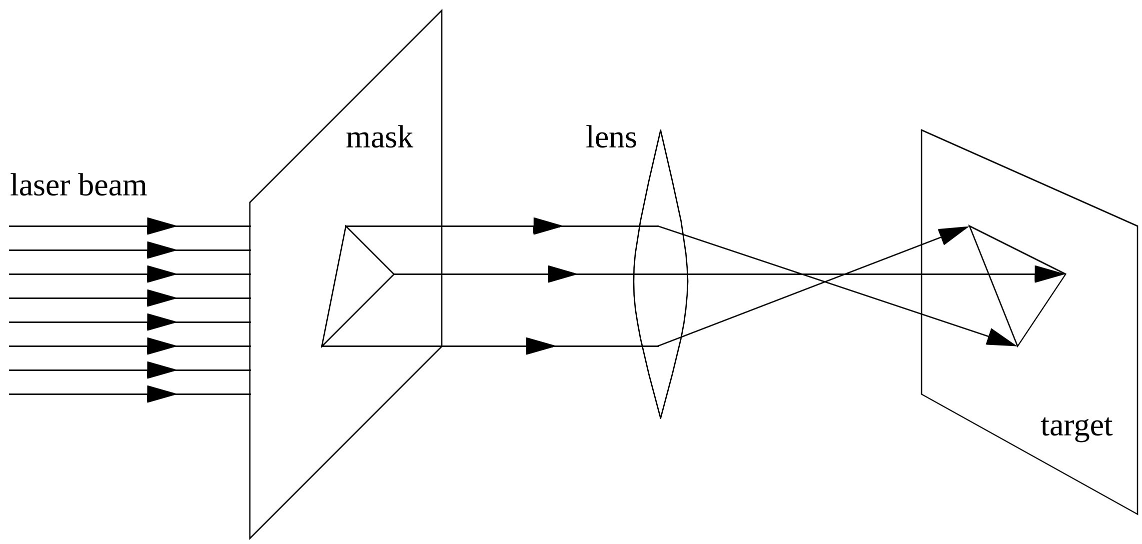
• By contrast, contact ink printing,
- is efficient, inexpensive, and quality is high when ink adheres
- not well suited to many new plastics because of ink bonding problems

• Laser marking is generally,
- permanent
- high contrast

- user friendly
- fast

• A laser is used to melt or evaporate surface material to create visible difference on the marked surface.

• Two methods are commonly used,
 scan - much like a television, the laser is vectored about the workpiece to create a complicated pattern.
 micromachining - has a beam that is passed through a mask, then through a lens to focus, and finally to the work surface where the mark is burned.



• Typical laser types used are,
 Nd:YAG
 TEA
 CO2

• Marked areas with micromachining can be up to 1 cm2, or more with the scan method.

• Good applications,
- date coders/part numbers/customer info
- frequent setups
- mark permanency

• In volume the laser system cost become lower per unit than ink.

• Advantages over ink are,
- no downtime to change inks
- elimination of many quality problems found in inks (e.g., ink permanency)
- elimination of special printing plates, etc.

• Typical setup time is 5-15 minutes for ink, but 1 minute for laser.

43.5 PRACTICE PROBLEMS

1. Lasers are good for marking objects when,
    a) Markings have complex mixtures of color.
    b) Cost is important.
    c) Markings require a long life.
    d) None of the above.

44. METALLURGICAL TREATMENTS

• We can perform operations that do not effect any visible or geometrical properties of a part, but will change the materials properties.

44.1 HEAT TREATING

• Main processes include,

Annealing - The metal is heated enough to recrystallize and held at the temperature for hours normally. Parts are cooled slowly.

Stress Relieving - The part is held for hours at a lower temperature than annealing so that the metal properties remain the same, but residual stress is reduced. The part is also cooled slowly.

Quench Hardening - The part is heated to Austenetizing range and then cooled rapidly using oil, water, etc. This created a very hard metal structure. Parts can be hardened in locations using inductive coils for location specific heating.

Tempering - After a hardening process (such as quenching) the part may be heated to beneath the Austenite range. This can be used to soften the part to a desired hrdness.

Carburizing - Soft steel parts can be heated for hours while coated in carbon. Carbon is absorbed into the surface and then the part is quenched. This gives a hard outside case, but the inside remains more ductile.

Carbon Nitriding - Similar to carburizing, except nitrogen is also absorbed in the surface. These parts have better surface wear properties.

Age Hardening - These parts are heated, quenched and then held at relatively low temperatures so that grains precipitate. The process is stopped using refrigeration. The result is parts with higher strength.

44.2 ION NITRIDING

• In a vacuum a part is heated and bombarded with nitrogen (or other) ions.

44.3 PRACTICE PROBLEMS

1. What is the purpose of heat treating?

2. How can steels be softened? How can steels be hardened?

3. How can aluminum be hardened?

4. How does case hardening work?

5. What techniques can be used to harden specific surfaces?

6. List and describe 6 different applications of heat treating.

7. Explain how the following changes the metals; a) recrystalization, b) smaller broken up grains, c) increase of carbon.

8. What is the difference between annealing and tempering?

9.

45. CASTING

• In casting we essentially start with an amorphous material, and hold it in shape while the material solidifies.

• Some of the typical casting processes and materials are listed below,

Flow	Process	Materials Cast	Mold Life - Mold Materials
Gravity	Bench Molding	Iron, steel, non-fer.	Single - green sand
	Ceramics Molding	Ferrous, non-ferrous	Single - cured sand
	Dip Molding	Plastic, metal, rubber	Permanent - metals
	Floor Molding	Iron, steel	Single - green sand
	Lost Wax/Investment	Metals	Single - plaster or sand
	Pit Molding	Iron, steel	Single - green sand
	Pouring	Concrete	Single - steel or wood
			Permanent - steel or wood
	Rotational Molding	Plastic, concrete, metal	Permanent - metals
	Shell Molding	Ferrous, non-ferrous	Single - cured sand
	Slush and Slip Molding	Non-ferrous	Permanent - iron and steel
		Ceramics	Single - plaster
Pressure	Blow Molding	Plastics, glass	Permanent - iron and steel
	Centrifuge	Metals	Single - sand
	Centrifugal Investment	Metals	Single - plaster
	Compression Molding	Thermosets	Permanent - iron and steel
	Continuous Casting	Steel, copper, aluminum	Permanent - none or graphite
	Die Casting	Non-ferrous, glass	Permanent - iron and steel
	Free Blowing	Thermoplastics	None
	Injection Molding	Plastics, rubbers	Permanent - metals
	Layup Molding	Fiberglass	Permanent - iron and steel
	Sand	Metal	Single/Permanent - Sand
	Straight-pressure mold.	Thermoplastics	Permanent - metals
	Transfer Molding	Thermosets	Permanent - iron and steel
	Vacuum Forming	Thermoplastics	Permanent - metal

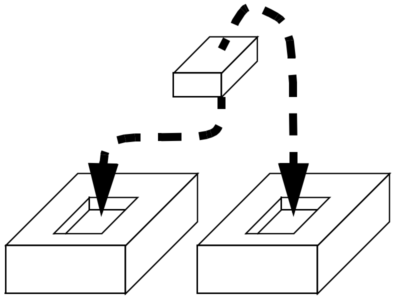
• A relative comparison of some casting techniques is given below,

Attribute	green sand	perman. mold	die	sand shell	CO2 core	ceramic/ invest.
Volume Cost	2	2	1	4	4	5
Batch Cost	1	4	5	4	4	3
Weights (lbs.)	no max.	100	30	250	tons	100
Thinnest Section	1/10”	1/8”	1/32”	1/10”	1/10”	1/16”
Typical Tol.	0.012”	0.03”	0.01”	0.010”	0.010”	0.01”
Surface Finish	3	2	1	2	3	1
Material Prop.	2	2	1	2	2	3
Complex Parts	3	3	2	2	2	1
Geometry Change	1	4	5	3	3	3
Materials	any	copper, low m.p.	alum, low m.p.	any	any	many

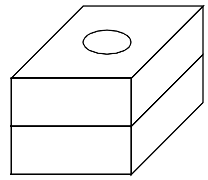
Legend
1 - very good
5 - very poor
m.p. - melting point

45.1 SAND CASTING

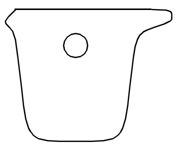
• Sand casting is one of the older techniques. In this form a mold is made from sand, and the part is cast into it. When the metal has hardened and cooled the part is removed, and the sand removed.



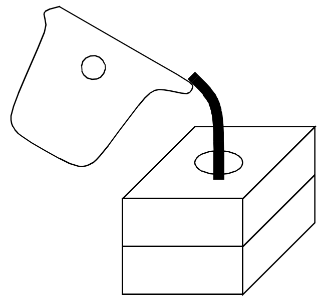
Pattern pushed into sand to make cavities A runner gate system will also be formed at this time. The same will harden



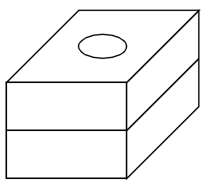
The patterns are matched with the pouring cup facing up



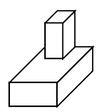
Metal is heated and prepared metallurgically. It is put into a cricible/tundish/etc for pouring



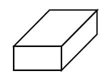
Molten metal is poured into the die



The part is allowed to sit and cool (large parts may take days)



The part is removed from the sand with the runner/gate/etc still attached



The part is finished and the surface is cleaned

• Typical stages of operation include,

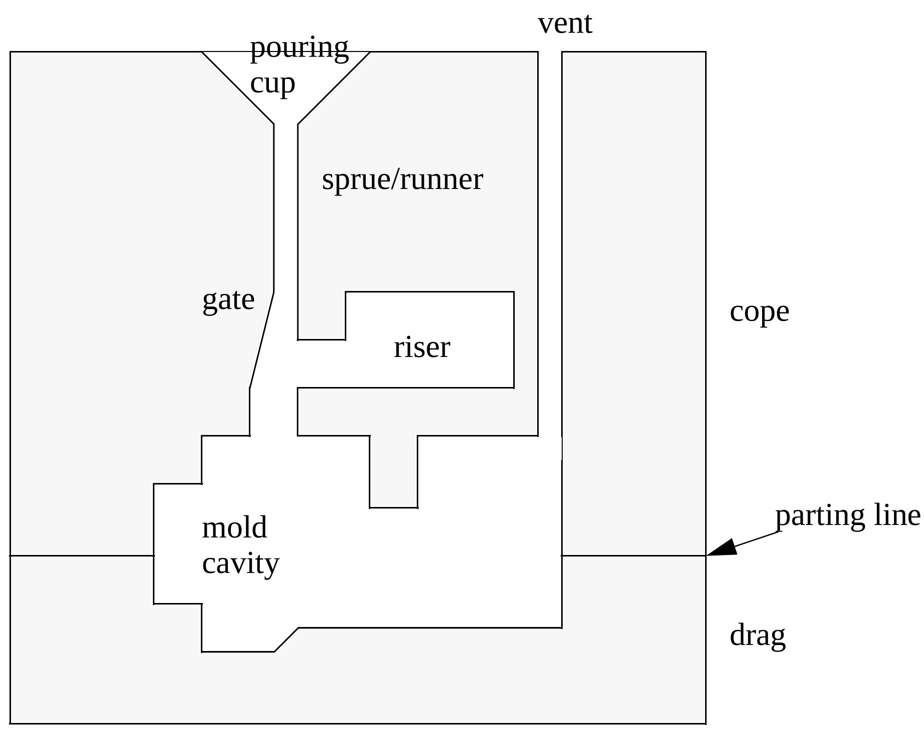
1. Patterns are made. These will be the shape used to form the cavity in the sand.
2. Cores may also be made at this time. These cores are made of bonded sand that will be broken out of the cast part after it is complete.
3. Sand is mulled (mixed) thoroughly with additives such as bentonite (clay) to increase bonding and overall strength.
4. Sand is formed about the patterns, and gates, runners, risers, vents and pouring cups are added as needed. A compaction stage is typically used to ensure good coverage and solid molds. Cores may also be added to make concave, or internal features for

the cast part. Alignment pins may also be used for mating the molds later. Chills may be added to cools large masses faster.

5. The patterns are removed, and the molds may be put through a baking stage to increase strength.
6. Mold halves are mated and prepared for pouring metal.
7. Metal is preheated in a furnace or crucible until is above the liquidus temperature in a suitable range (we don’t want the metal solidifying before the pour is complete). The exact temperature may be closely controlled depending upon the application. Degassing, and other treatment processes may be done at this time, such as removal of impurities (i.e. slag). Some portion of this metal may be remelted scrap from previously cast parts - 10% is reasonable.
8. The metal is poured slowly, but continuously into the mold until the mold is full.
9. As the molten metal cools (minutes to days) the metal will shrink. As the molten metal cools the volume will decrease. During this time molten metal may backflow from the molten risers to feed the part, and maintain the same shape.
10. Once the part starts to solidify small dendrites of solid material form in the part. During this time metal properties are being determined, and internal stresses are being generated. If a part is allowed to cool slowly enough at a constant rate then the final part will be relatively homogenous and stress free.
11. Once the part has completely solidified below the eutectic point it may be removed with no concern for final metal properties. At this point the sand is simply broken up, and the part removed. At this point the surface will have a quantity of sand adhering to the surface, and solid cores inside.
12. A bulk of the remaining sand and cores can be removed by mechanically by striking the part. Other options are to use a vibrating table, sand/shot blaster, hand labor, etc.
13. The final part is cut off the runner gate system, and is near final shape using cutters, torches, etc.. Grinding operations are used to remove any remaining bulk.
14. The part is taken down to final shape using machining operations. And cleaning operations may be used to remove oxides, etc.

45.1.1 Molds

• The basic components found in many molds are shown below,



• The terms for the parts of a mold are,

pouring cup - the molten metal is poured in here. It has a funnel shape to ease pouring accuracy problems.

runner/sprue - a sprue carries metal from the pouring cup to the runners. The runners distribute metal to the part.

gate - a transition from the runner to the cavity of the part

riser - a thermal mass where excess metal will remain in a liquid state while the part cools. As the cooling part shrinks, the molten metal in the riser will feed or fill in the shrinkage. Risers can also be used to collect impurities that rise in molten metal.

mold cavity - this is the final shape of the part.

vent - a narrow escape passage for gases that would otherwise be trapped in the mold.

parting line - a line of separation that allows the mold (made in two pieces) to be put together to make a full cavity. Note that this line does not have to be a straight line, and is often staggered to make the mold making easier.

cope - the upper part of a casting mold

drag - the lower part of a casting mold

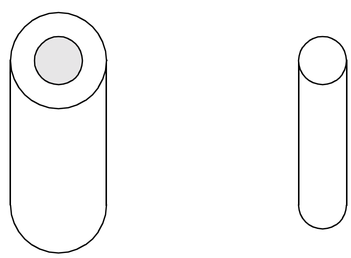
• There are a number of interesting points about patterns,

- molds are made by compacting sand around the shape of the pattern.
- patterns are made of wood, metal and plastics - the material must be stronger if a large number of molds are to be made.
- a parting agent can be used on a pattern to allow easy removal after the mold is made.
- pattern types include

    one piece patterns (loose or solid patterns) - low quantity simple shapes

split patterns - for complex shapes made in two patterns for each half of the part.
match plate - the split patterns are mounted in a single plate. This allows gating on the drag side to match up with the runners on the cope.
- design of the patterns should include consideration of shrinkage
- a slight taper should be added to the sides all patterns this will make them easy to remove from the completed mold. i.e. a cone is easier to remove than a cylinder.

• Cores are typically used for more complex shapes. Some point of interest,
- Cores allow features that could not be easily formed into a sand core.
- Cores are made with techniques similar to those for making sand molds.
- The cores may need structural support in the mold - these metal supports are called chaplets.
- The cores are added when the cavity are made, and they act as part of the mold during casting, but they are rigid enough to allow internal features on parts.
- Cores can be made easily in automated settings.



A core is used to keep the hollow inside the part

• A mold might undergo a hardening process,
green sand - no hardening, just moist
cold-box - binders are mixed with the sand to increase dimensional accuracy
no-bake - liquid resin binders harden the sand at room temperature
skin-dried - the sand is hardened by drying in an oven or air. Higher strength, but distortion and lower collapsibility.
baking - the molds are baked before casting to harden the entire mass

• When the pattern and cores have been inserted into the sand it is compacted. There are a number of techniques for doing this,
Squeeze Molding Machines - automatically insert and compact sand. The processes used are designed to produce a uniform compaction. Jolting is sometimes used to help settle the sand. These molds are made in flasks.
- conventional flat head
- profile head
- equalizing pistons
- flexible diaphragm
Vertical Flaskless Molding - the molds halves are made by blowing sand against a vertical mold. High production rates are possible.

Sandslingers - A high speed stream of sand into the flask tends to pack the sand effectively.
Impact molding - an explosive impulse is used to compact the sand. The mold quality with this technique is quite good.
Vacuum molding - an envelope of plastic is created about the sand using plastic sheeting. Air is drawn from the sand, and the vacuum leads to compaction.

45.1.2 Sands

• The sands used tend to fall into the following categories,
naturally bonded (bank) - less expensive
synthetic (lake) - this sand can have a variety of controlled compositions.

• Types of sand include,
- Zircon ($ZrSiO_4$) - low thermal expansion
- Olivine (Mg_2SiO_4) - low thermal expansion
- Iron Silicate (Fe_2SiO_4) - low thermal expansion
- Chromite ($FeCr_2O_4$) - high heat transfer

• The sand effects the following aspects of the casting,
granule shape - smaller and rounder grains produce a better casting surface.
granule size - a coarse grained sand will be porous and allow gases to escape during casting. a fine grained sand leads to a stronger mold.
collapsibility - if the sand can shift during cooling of the part it will reduce stress tears and cracks

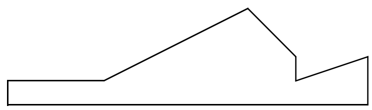
• Green sand molding refers to a slightly wet condition of the sand (much like ‘green wood’). At the right level of humidity the moisture will increase sand binding. But in excess this moisture expand when heated during pouring and blow metal back out of the mold (i.e. explosion). This is one of the least expensive molding techniques).

45.2 SINGLE USE MOLD TECHNIQUES

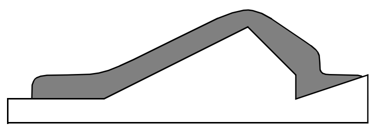
45.2.1 Shell Mold Casting

• The basic process for these molds is,
1. Create two mating patterns of desired shape.
2. Coat the molds with a shell (sand and binders, such as a resin) until desired thickness and other properties are obtained.

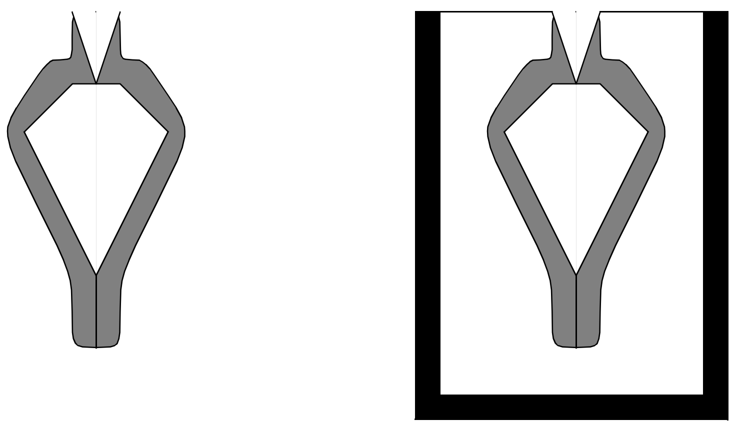
3. Cure the molds and remove the patterns.
4. The mold halves are mated and held firm while metal is poured.
5. The final part(s) is removed.



Start with matching patterns (the pattern is shown with diagonal lines)



A sand is used to coat the molds, and it is bonded to make shells



The pattern halves are mated, and then backed up to complete the mold

• This technique can be very economical.

• Special care must be taken to assure venting for gasses, as the mold media is less porous.

• This method can easily use cores and chills to make complex molds.

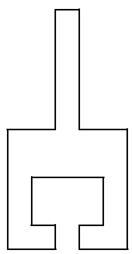
• Graphite molds can be used for materials that would normally react with other materials used for the molds.

45.2.2 Lost Foam Casting (Expandable Pattern)

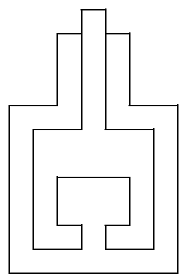
• This process has a number of basic steps,

1. Make a mold for producing styrofoam patterns.

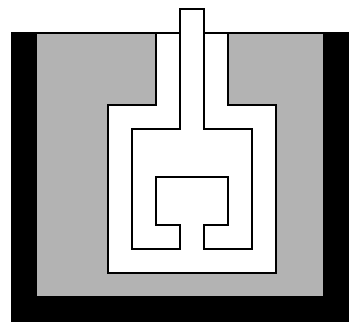
2. Make styrofoam patterns using inject molding of expanded polystyrene foam beads (or another low density monomer foam) This process can be automated.
3. Glue the parts foam patterns together, and glue to sprue/runner/gate systems as required.
4. For high quality surface finish the parts may be coated with a ceramic slurry and hardened in a drying oven.
5. Place the pattern in sand, taking care to compact the sand about the pattern.
6. Cast metal into the pattern. The foam will evaporate, and escape through the normal routes gas evacuates through.
7. Wait until the part is hard, and remove from the sand.
8. If a ceramic coating was used this can be removed using impact, vibration, or abrasive techniques as appropriate.



A styrofoam pattern is made

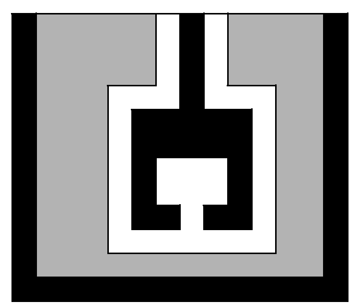


The pattern is coated with a refractory coating and dried



The foam pattern is packed in sand

Molten metal is cast in, and the styrofoam evaporates. The metal takes the shape of the refractory coating



• This process can be automated, and can be very inexpensive in quantities.

• Complex parts can be made with relative ease by gluing together foam pieces.

45.2.3 Plaster Mold Casting

• This technique is basically,

1. Create a two part pattern.

2. A mold material is used that is a plaster of paris type mixture (fast setting) to make two cavities. This may have some additives to improve properties. Foamed plaster may be used to increase permeability.
3. After setting these cavities will be dried in an oven to remove moisture.
4. The Antioch process is optional and increases mold permeability by dehydrating in an autoclave, and rehydrating for a number of hours.
4. The mold halves are then mated and heated.
5. After reaching adequate heat levels the molten metal is poured. Mold porosity is low so pressure or vacuum must be used to encourage complete filling of the mold.
6. The final part is removed and cleaned

• This technique is known for its high level of dimensional accuracy.

45.2.4 Ceramic Mold Casting

• Also known as ‘cope and drag investment casting’.

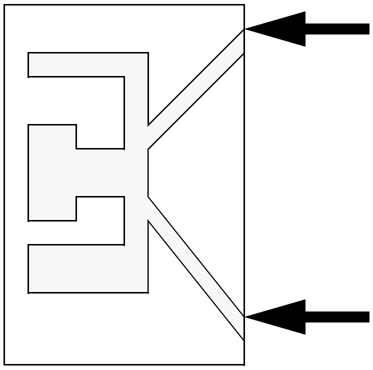
• The basic process is,
1. A wood or metal pattern is placed in a flask and coated with a slurry of zircon and fused silica combined with bonding agents.
2. The mold is removed, cleaned and baked. The shells may be used as given, or they may have other materials, such as clay put on as backing materials.
3. The molds are then used as normal.

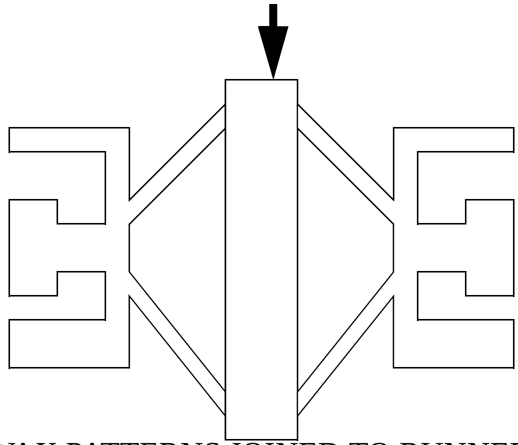
• This can make high temperature material parts.

45.2.5 Investment Casting

• The basic steps are,
1. An expendable mold of a part is made in wax, plastic, etc.
2. The part has a gate and runner attached to it, and all are dipped in a ceramic slurry.
3. The slurry is hardened, and the core is melted and/or burned out.
4. The core is burned out and the mold is preheated to the temperature of the molten metal
   - 644°C for aluminum
   - 1040°C for ferrous alloys
   - etc.
5. Molds are filled by pressure, vacuum or centrifugal force.
6. After cooling, the mold is broken off, the sprues are cut off, and stubs are ground off.

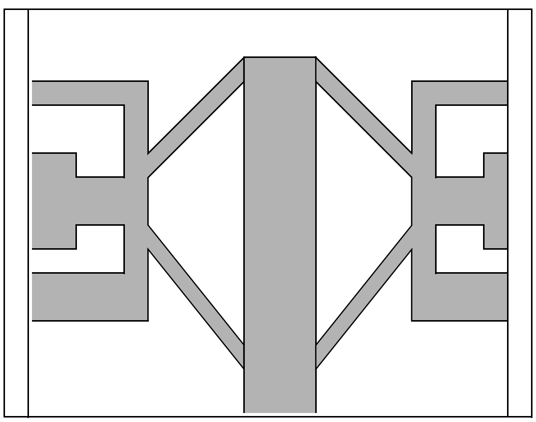
WAX PATTERN MOLDED



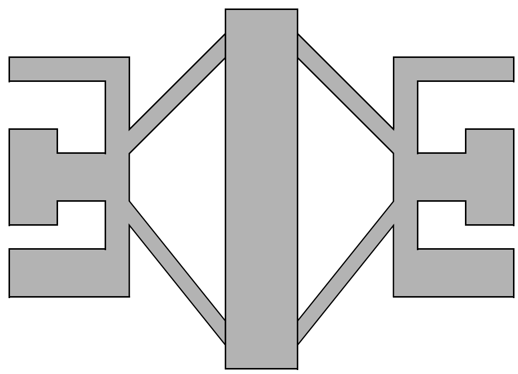


WAX PATTERNS JOINED TO RUNNER

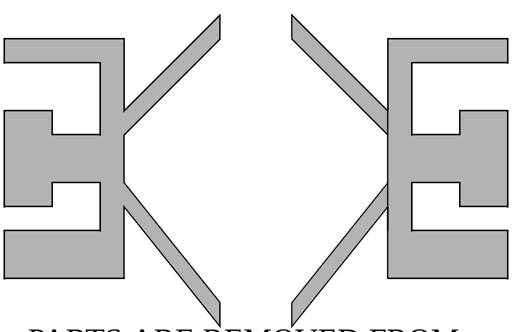
The waxcore is molded in some other place, and the patterns are created XXXXXX



WAX PATTERNS COATED IN CERAMIC, WAX IS MELTED OUT, THE SHELL IS DRIED, AND PLACED IN SAND



METAL IS CAST INTO THE SHELL AND ONCE SOLID REMOVED FROM THE SAND



PARTS ARE REMOVED FROM THE RUNNER SYSTEM

PARTS ARE FINISHED

• Many parts can be made at the same time by attaching them to a common gating system.

• Parts can be glued together to make shapes that would normally be too complex to mold.

• Typical methods used are,
  - cast iron
  - steel
  - aluminum alloys
  - brass
  - bronze
  - magnesium
  - zinc

• The die used to make the mold cores can be used for thousands of parts.

• Typical large applications are,
  - large propellers
  - large frames
  - nozzles
  - cams
  - valve parts

• Typical small applications are,
  - dental
  - jewelry
  - orthopedic surgical implants
  - camera components

• Advantages,
  - fine details can be made
  - thin sections are possible
  - high accuracy
  - weights from <1 ounce to > 100 lb.
  - any castable metal can be used
  - no parting lines
  - good surface finish (60-220 μ in.)
  - can be automated
  - many parts can be made at once providing lower per piece cost
  - high melting point metals can be used

• Disadvantages,
  - less strength than die cast parts
  - process is slow
  - changes to the die are costly
  - more steps are involved in production

45.3 MULTIPLE USE MOLD TECHNIQUES

45.3.1 Vacuum Casting

• The basic process is,

1. A mold is made using sand, urethane, and amine vapors to cure.
2. The mold is mounted on a moving head.
3. The head is lowered into molten metal in an induction furnace so that the lower face of the mold is submerged.
4. Vacuum is applied to the mold and metal is drawn up to fill the cavity.

• This process is relatively inexpensive and can be automated.

• Thin walls, down to 0.02” are possible.

• The process can be used effectively with reactive metals.

45.3.2 Permanent Mold Casting

• The basic process is,

1. A metal mold is made in two halves.
2. The mold is then coated with a refractory coating, or sometimes graphite is used instead. This acts as a thermal barrier, and as a parting agent.
3. Cores are then added as required.
4. The mold halves are mated and preheated to about 300-400°F.
5. Low melting point molten metal is poured into the dies.
6. Water channels, or heatsink fins are used to cool the mold quickly.
7. The mold is opened, and ejector pins are used to force the part out of the mold - this leaves small circular depressions on the surface of the part.
8. the sprue is removed, and the stub is ground off.

• The mold cavity is typically coated with a refractory coating to reduce heat damage, and ease part removal after casting. The materials also help control the cooling rate of the casting. Typical materials include,

- sodium silicate and clay
- sprayed graphite

• Molds are machined, including the cavity and gates. Typical mold materials include,

- cast iron and alloyed cast irons

- steel
- bronze
- graphite
- refractory metal alloys

• Typical core materials include,
  - oil-bonded sand
  - resin-bonded sand
  - plaster
  - graphite
  - gray iron - most common
  - low-carbon steel
  - hot work die steel

• Low melting point metals can be cast
  - aluminum
  - zinc
  - magnesium alloys
  - brass
  - cast iron

• Movable sections can be used to allow removal of cast parts.

• Can be used for thousands of parts before mold is replaced or repaired.

• Part sizes are from a few ounces to a hundred pounds.

• Typical applications are,
  - pistons/cylinders/rods
  - gears
  - kitchenware

• Advantages,
  - the mold can be chilled to speed cooling
  - good surface finish
  - good dimensional accuracy
  - only one mold is required

• Disadvantages,
  - limited numbers of alloys can be used
  - complex shapes cannot be cast
  - mold production is time consuming and costly
  - mold sizes are limited

45.3.2.1 - Slush Casting

• Permanent mold casting can be used to produce hollow parts without using cores.

• In this process the mold is filled as normal, and solidification begins at the outer surface and moves inwards. After a short period of time the mold can be turned over, and the molten metal inside will run out. This leaves a thin shell in the mold.

45.3.2.2 - Pressure Casting

• In this process the normal permanent mold process is used, except instead of pouring molten metal, it is forced into the die under a moderate pressure or pulled in using vacuum). This pressure is maintained until the part has solidified.

• The constant pressure allows for filling of the mold as it shrinks.

45.3.2.3 - Die Casting

• The basic process is,

1. two permanent mold halves of a die (mounted in a press) are brought together.
2. the molten metal is injected through a runner and gate with pressures up to 100 ksi - 2000-5000 psi is common.
3. air escapes into overflow wells, and out vents, and metal fills the molds
4. the mold is chilled, and the injected metal freezes
5. the mold is separated, and knockout pins eject the part
6. the parts are cut off the runners and sprues

• Used for low melting point (non-ferrous) metals such as,
- zinc
- aluminum
- magnesium
- copper
- lead
- tin

• Can produce complex shapes at mass production rates.

• Metal dies,
- must withstand high pressures
- die life is shortened by extreme temperature fluctuations

- dies often made with carbon or special alloys
- multiple cavities can be used in the die

• Applications,
- automotive parts
- appliances
- office machines
- bathroom fixtures
- outboard motors
- toys
- clocks
- tools

• Die casting machines can use,
- hot chambers with a plunger - a reservoir of molten metal is used to directly feed the machine.
- a cold chamber - metal is ladled into the machine for each shot.

• Hot chamber machines are,
- good for low temperature zinc alloys (approx. 400°C)
- faster than cold chamber machines
- cycle times must be short to minimize metal contamination
- metal starts in a heated cylinder
- a piston forces metal into the die
- the piston retracts, and draws metal in

• Cold chamber machines,
- casts high melting point metals (>600°C)
- high pressures used
- metal is heated in a separate crucible
- metal is ladled into a cold chamber
- the metal is rapidly forced into the mold before it cools

• All die casting processes require a large press to hold mold halves together during a cycle.

• Advantages,
- intricate parts possible
- short cycles
- inserts feasible
- cycles less than 1 minute
- minimum finishing operations
- thin sections, high tolerances, good surface finish

• Disadvantages,
- metal die is costly
- porous parts

- not suited to large parts
- long setup times
- $5000-200,000 for machine
- metal melting point temperature must be lower than die

45.3.3 Centrifugal Casting

• The basic process is,

1. a mold is set up and rotated along a vertical (rpm is reasonable), or horizontal (200-1000 rpm is reasonable) axis.
2. The mold is coated with a refractory coating.
3. While rotating molten metal is poured in.
4. The metal that is poured in will then distribute itself over the rotating wall.
5. During cooling lower density impurities will tend to rise towards the center of rotation.
6. After the part has solidified, it is removed and finished.

• There are three variants on this process,

true centrifugal casting - long molds are rotated about a horizontal axis. This can be used to make long axial parts such as seamless pipes.

semicentrifugal casting - parts with a wide radial parts. parts such as wheels with spokes can be made with this technique.

centrifuging - the molds are placed a distance from the center of rotation. Thus when the poured metal reaches the molds there is a high pressure available to completely fill the cavities. The distance from the axis of rotation can be increased to change the properties

• Centrifugal and semicentrifugal casting used for axisymmetric parts (internally).

• Parts from 6” to 5’ in diameter can be made, but typical diameters are 10’ to 30’.

• Long tubes can be made that could not normally be rolled.

• Typical metals cast are,

- steel
- nickel alloys
- copper
- aluminum

• Typical applications are,

- train wheels
- jewelry
- seamless pressure tubes/pipes

• Advantages,
  - good uniform metal properties
  - no sprues/gates to remove
  - the outside of the casting is at the required dimensions
  - lower material usage
  - no parting lines
  - low scrap rates

• Disadvantages,
  - extra equipment needed to spin mold
  - the inner metal of the part contains impurities

45.3.4 Casting/Forming Combinations

• These processes basically casting molten metal, but the use mechanical force to reshape.

45.3.4.1 - Squeeze Casting

• The basic process is,
  1. Molten metal is poured into an open face die.
  2. A punch is advanced into the die, and to the metal.
  3. Pressure is applied to the punch and die while the part solidifies. This pressure is lower than normally required for forging.
  4. The punch is retracted, and the part is knocked out with an ejector pin.

• This method overcomes problems with feeding the die, and produces near net, highly detailed parts.

45.3.4.2 - Semisolid Metal Forming

• The basic process is,
  1. A metal is heated until it has thixotropic properties (when agitated viscosity decreases).
  2. The metal is poured into a die in a semi-solid state, and the mold is filled.
  3. The metal hardens.

• This can produce better metal qualities in net shape parts requiring no finishing operations.

45.3.5 Single Crystal Casting

• The process is effectively,

1. Prepare a mold so that one end is a heated oven, and the other end chilled. The part should be oriented so that the cooling happens over the longest distance.
2. Cast metal into the mold
3. Solidification will begin at the chill plate. These dendrites will grow towards the heated end of the part as long dendritic crystals. The part is slowly pulled out of the oven, past the chill plate.
4. Remove the solidified part.

• Parts made of a single crystal can have creep and thermal shock resistance properties.

• There are two variants to this technique,

directionally solidified - in this case the dendrites grow from the chill plate towards the other end.

single crystal - a helical constriction is used so that instead of parallel dendrites, only a single crystal is formed in the blade.

45.4 OTHER TOPICS

45.4.1 Furnaces

• Some of the types include,

- coreless induction - magnetic fields induce eddy currents throughout the entire furnace, resulting in melting
- core induction - magnetic fields induce eddy currents in a small section of the furnace, resulting in melting
- gas fired crucible - uses ignited gas and air to heat crucible in enclosed oven
- electric arc - arcs are used to heat metals
- cupolas - layers of metal and ore are placed in this refractory lined vessel, and ignited to produce large volumes of metal.

45.4.2 Inspection of Casting

• General problems with castings are,

- cavities

- projections
- discontinuities
- defective surfaces
- incomplete
- incorrect dimensions
- inclusions

• Typical inspection methods are,
  - polishers & microscopes to look at microscopic structures
  - metal analyzer to determine chemical composition
  - X-rays are used to examine hidden cracks and blowholes

45.5 Design of Castings

• When designing casting the most important consideration is the effects of shrinkage during cooling. Other important factors include metal flow, and porosity.

• Some general rules of thumb are,
  - Avoid sharp corners - they can lead to hot tearing during cooling.
  - Use fillets cautiously - they lead to stresses as they shrink a radius of 1/8” to 1” are acceptable.
  - Avoid large masses - they will cool more slowly, and can lead to pores and cavities in the final part. Cores can be used to hollow out these large volumes. Metal padding ‘chills’ can also be placed inside the mold near large masses to help increase cooling rates.
  - Use uniform cross sections -this will keep the cooling rate relatively uniform and avoid stresses.
  - Avoid large flats - large flat areas tend to warp.
  - Allow some give as the part cools - by allowing the shrinkage of one part to deform another slightly, the internal stresses will be reduced. Figures of 1-2% shrinkage are common.
  - Put parting lines near corners - this will hide the flash.
  - Straight Parting Lines - where possible a straight parting line will allow easier mold making.
  - Use a Draft angle - A small angle of 0.5-2° on the vertical walls will make the pattern easier to remove.
  - Machining Allowances - allow excess material for later machining of critical dimensions
  - Wide Tolerances - because shrinkage occurs as the part cools it will be very hard to keep tight tolerances.
  - Stress Relieve When Needed - Stress relief can reduce the effects of non-uniform cooling.
  - Avoid thin sections - These will be very hard to fill, and will tend to harden quickly.
  - Avoid internal features - These will require extra steps in mold making, and may create

metal flow problems.

45.6 REFERENECES

Lewis, R., His previous course notes for MEC015 have basically been adapted to what is shown here.

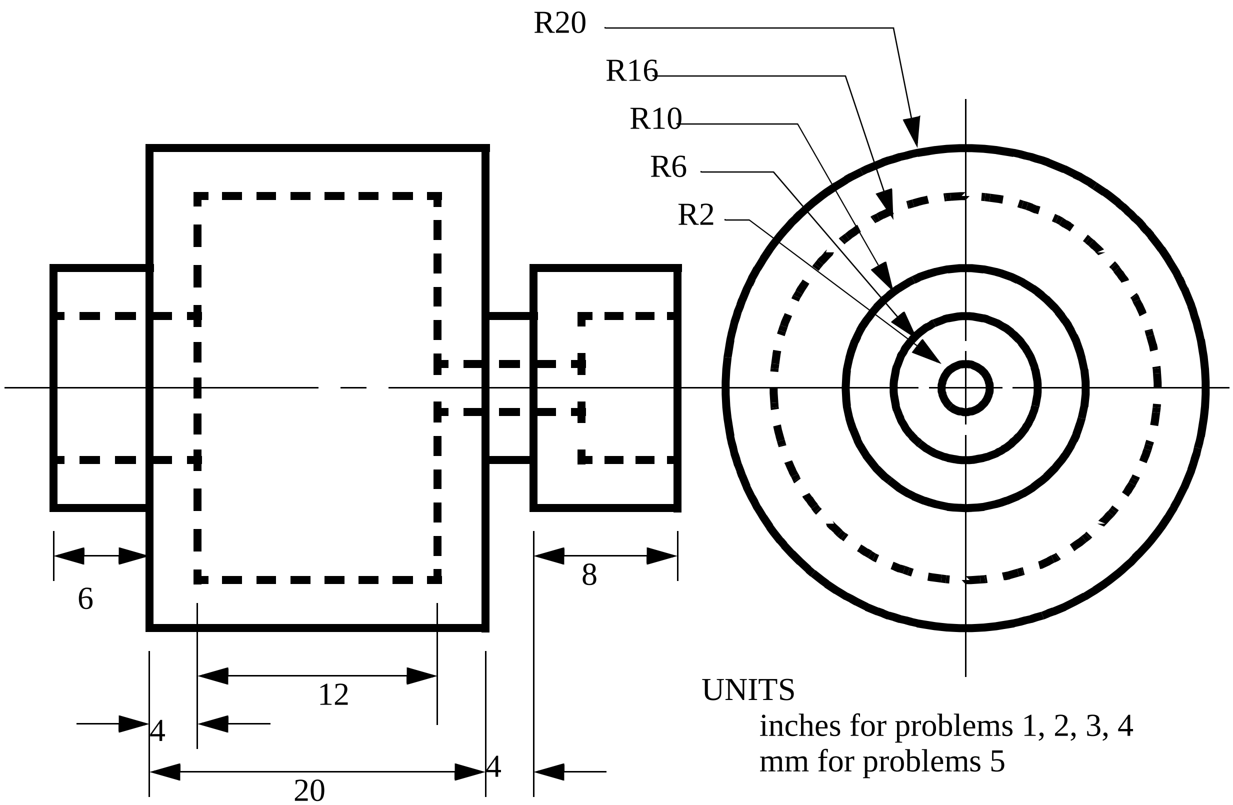
Kalpakjian,

Krar,

45.7 PRACTICE PROBLEMS

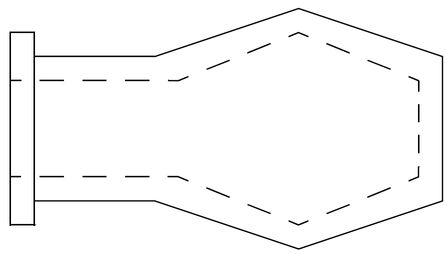
1. TRUE / FALSE - Investment casting is well suited to producing many parts at once.

2. The part below will be referred to in a number of questions. The drawings are not to scale but they do show an axisymmetric part (i.e., round) with a hollow internal core. The drawing is not to scale, but the rough dimensions are given. You are free to make assumptions (they must be stated) where necessary.



a) Describe in details the steps required to make this part using sand casting.
b) List the steps in detailed to make this part with investment casting.
c) List other casting processes that could be used to make this part. Provide your opinion of relative ranking (e.g., 1 to 5) with a general reason for each.
d) List other casting processes that should not be used to cast this part. Provide a reason why not.
e) If the part is to be made with injection molding, what special considerations would be required?
f) List appropriate techniques for making this part using thermoplastics. Give a relative ranking (e.g., 1 to 5) with reasons.
g) List types of composite manufacturing techniques that are, and are not suitable for making this part. Give reasons why.

3. a) Design a sand casting mold for the jar shaped part below. Include risers, gates, runners, etc., Indicate the parting line between the cope and drag. It will be filled from the side as drawn.



b) List and explain why 2 features of this part would be hard to cast.

4. Suggest parts that are best suited to produce with the following casting techniques. You must briefly state why is best suited to the method.
a) Centrifugal lost wax investment casting
b) floor/pit casting
c) die casting
d) true centrifugal casting

5. Describe the procedures that would be involved in making a bronze statue. Which casting processes would be suitable? Why?

6. Why are castings normally cooled slowly?

7. How does the microstructure of a casting relate to the cooling rate?

8. What factors will result in a cast part not matching the pre casting mold shape?

9. Suggest two casting methods that would be suitable for making small toy cars? Indicate which would be better and why.

10. Suggest two casting processes would be well suited to making a large casting of a 4 foot tall ornament? Indicate the benefits and limitations of each.

11. How can hot tearing be avoided in castings?

12. Why should risers be located near large masses in cast parts?

13. How can chills help deal with large masses in a mold?

14. List and describe 8 different casting applications.

15. Identify design features that will cause problems when casting.

16. What are the major advantages and disadvantages of casting over other manufacturing pro-

cesses.

17. Why is a complex runner/gate system used in sand casting. Why is it important to pour slowly and continuously?

18. Why is it important to allow gases to escape? Are there any processes where this would be more important? Which processes eliminate this problem.

19. Why is moisture such a significant problem in casting?

20.

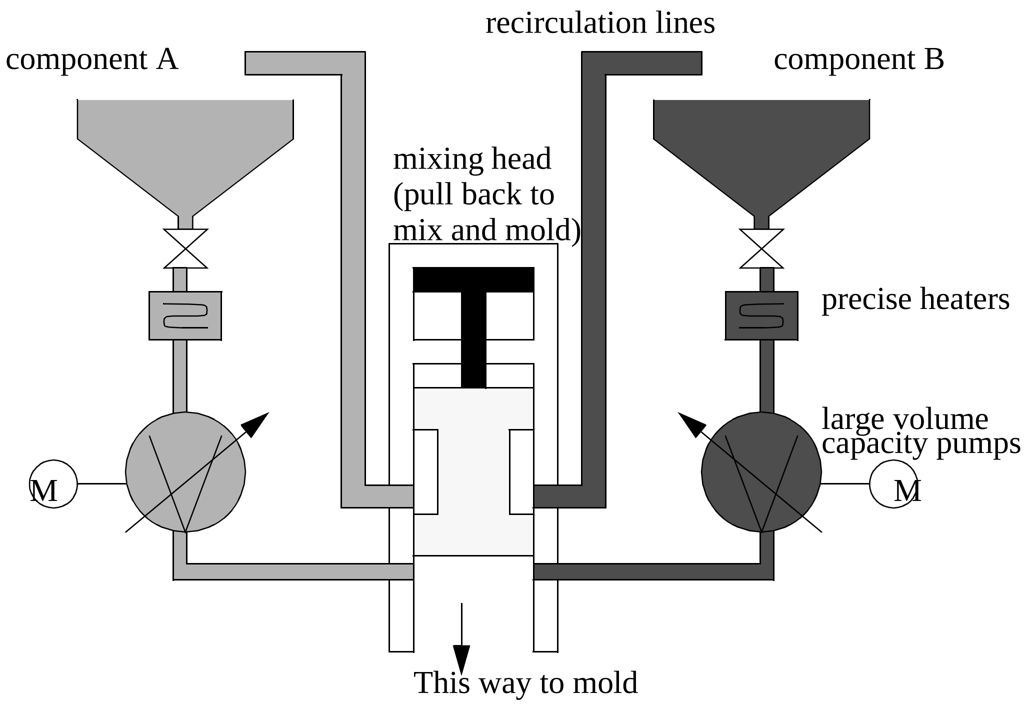
46. MOLDING

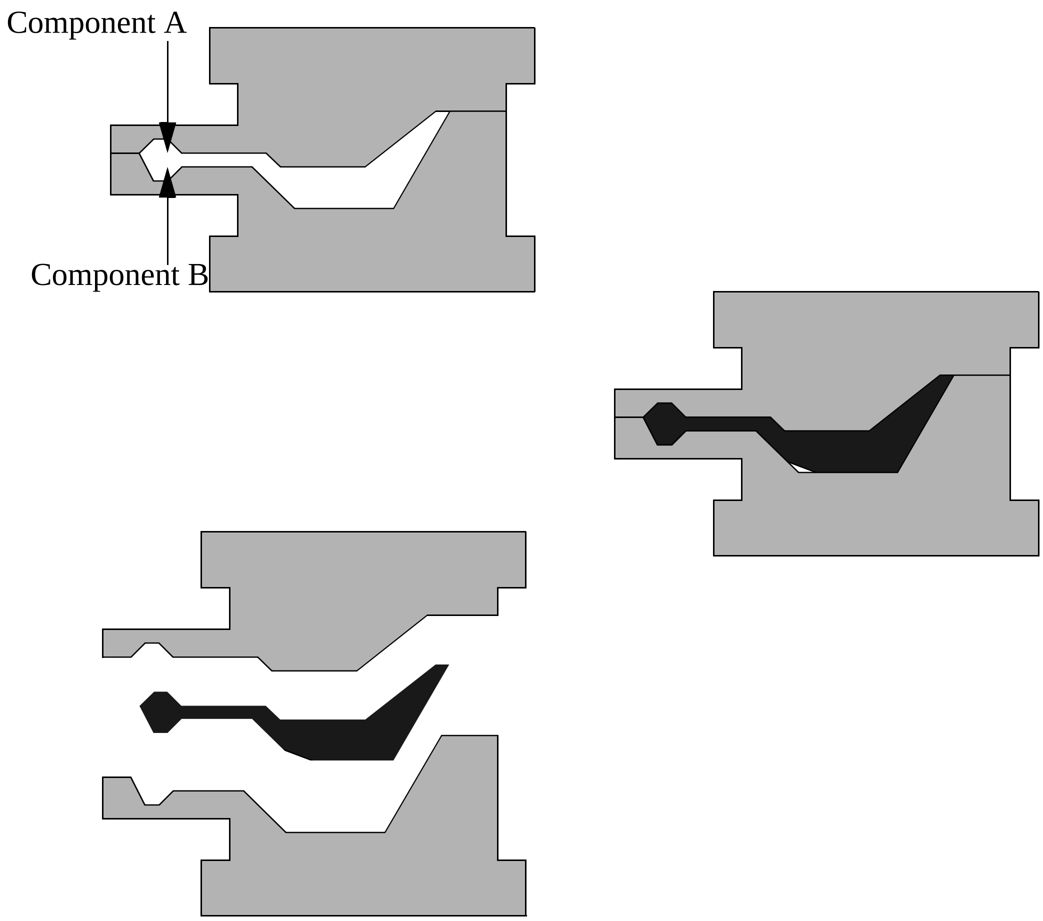
• Plastics can be categorized as follows,

Calendering	Sheet Forming	Drape	
		Pressure	
		Vacuum	
Casting	Foaming		
	Rotational Molding		
	Solvent	Shell	
		Slush	
Coating	Brush		
	Dip		
	Fluidized Bed		
	Roll		
	Spray		
Joining			
Laminating & Extruding	Blow Molding		
	High Pressure		
	Low Pressure	Filament Winding	
		Lay Up	
		Molding	Bag Pressure
			Bag Vacuum
			Centrifugal
			Matched Metal Die
		Preforms	Directed Fiber
			Plenum Chamber
			Water Slurry
		Spray Up	
	Sheet Forming	Drape	
		Pressure	
		Vacuum	
Machining			
Molding	Cold		
	Compression		
	Injection		
	Transfer		

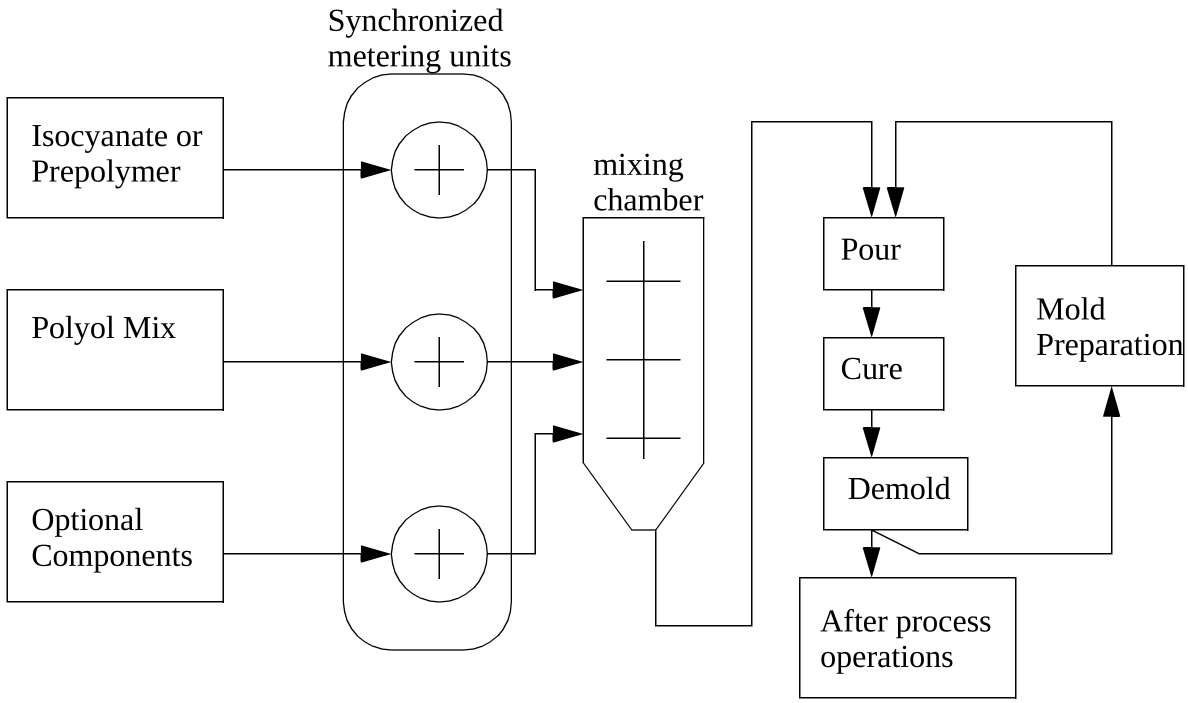
46.1 REACTION INJECTION MOLDING (RIM)

• Basic Principle - A mold is brought together, and a multipart thermosetting polymer is mixed and injected. After the part sets, the mold is opened, and the part is removed. Post curing may be used.

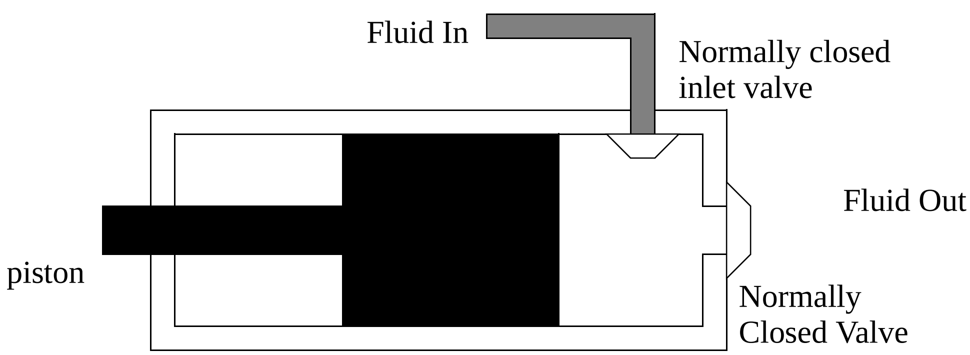




• Features:
- Very little energy is required, most energy is provided by the chemical reaction.
- Parts up to 100 lb produced.
- Surfaces don’t have flow lines found in traditional injection moulding.
- RIM materials tend to be low weight, corrosion resistant, and variable properties can be obtained by additives and ratio adjustment.
- RIM machines use lower pressures, and are therefore less expensive.
- Typical parts are; bus bumpers, large electronics cases, shoes, etc.
- Fillers can be used to increase strength.
- The basic process involves mixing the raw components.

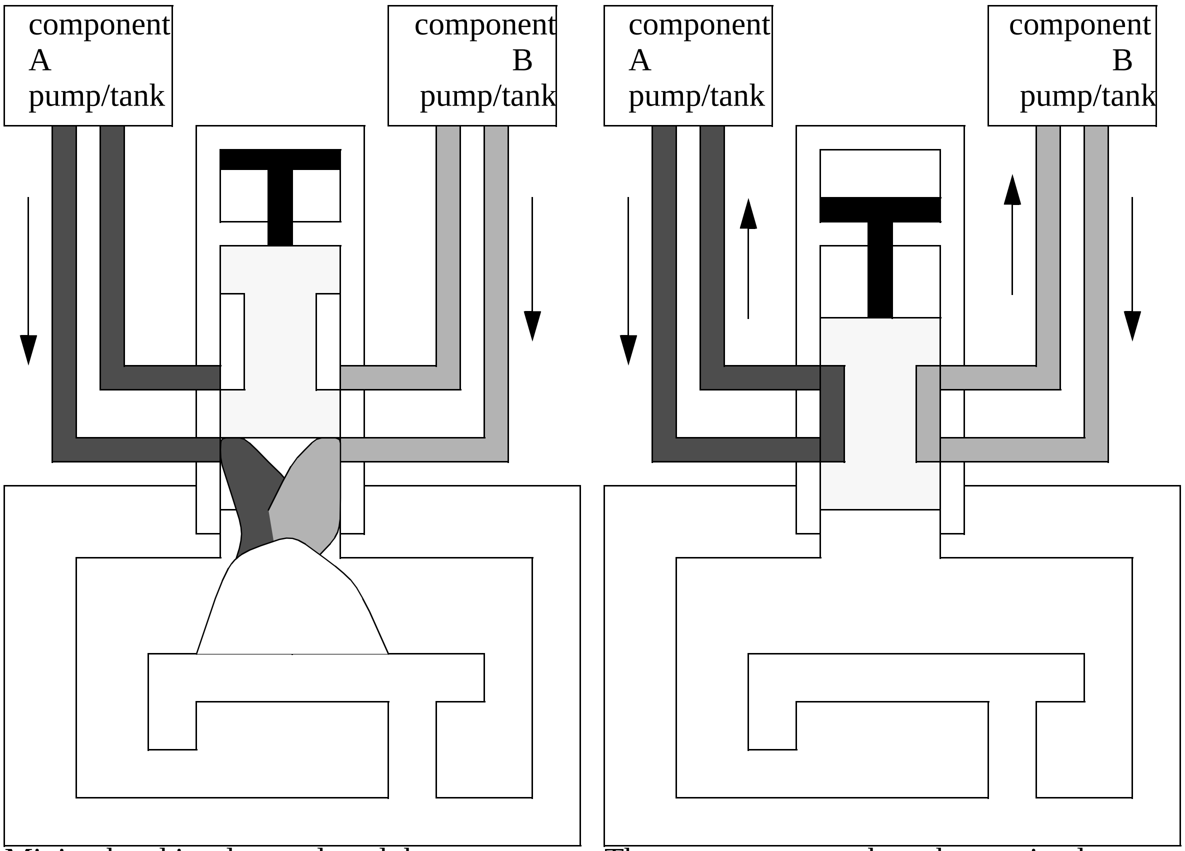


- Metering and mixing are critical
  - special metering pumps are required for the components to maintain material properties.



In this common form of piston pump, the piston rod is drawn back creating suction that holds the valve closed, and pulls fluid into the chamber. When the cylinder is full of fluid the piston motion is reversed, creating a pressure, and forcing the inlet vale closed, and the outlet valve open, and the fluid is pumped out. The fluid volume can be controlled by using the cylinder size, and piston strokes

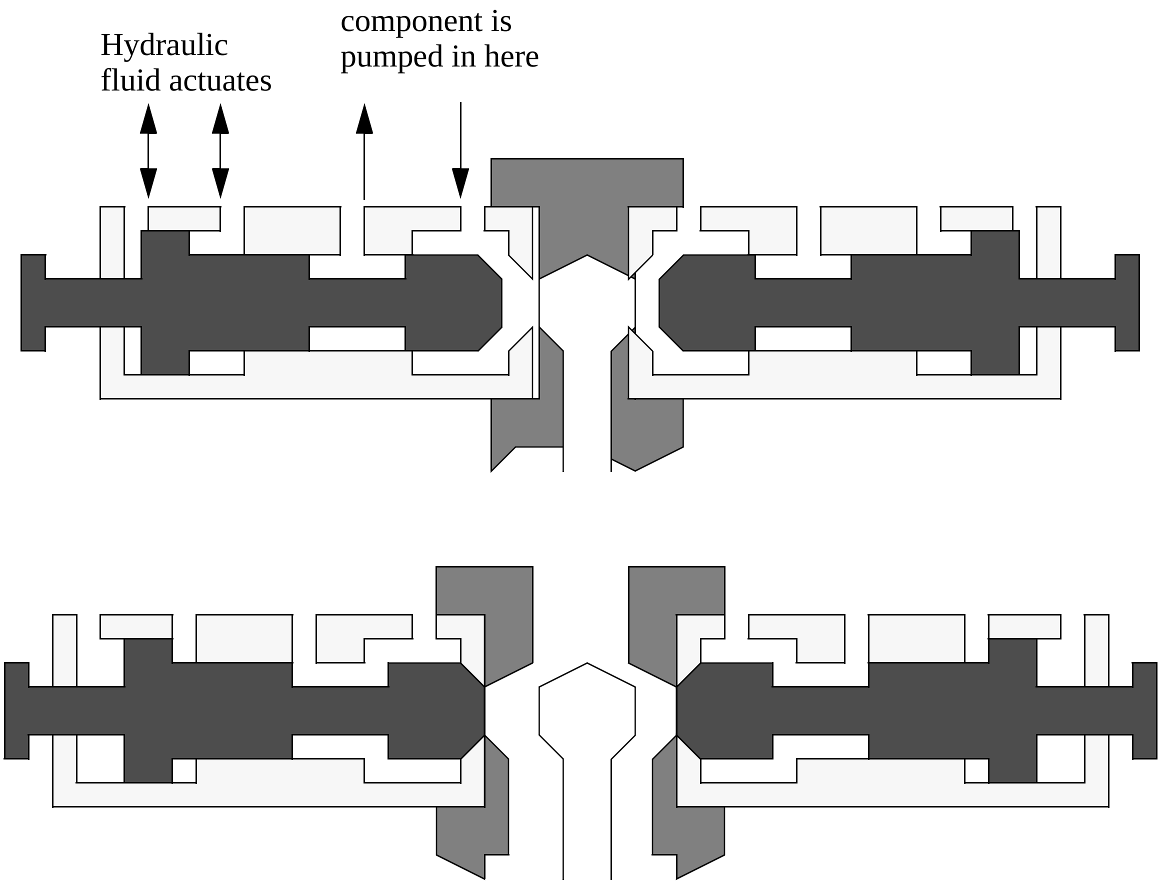
- mixing must thoroughly mix the components at high speed, and inject them without becoming clogged when the mixture sets.



Mixing head is advanced, and the two components are mixed, and they pour into the mold

The two component have been mixed, or the mold is empty, and the mixing head is retracted, allowing the components to recirculate

• While the previous mix head is for a runnerless system, it is also common to have an extra component that is between the mix head and the part (the runner).



• An aftermix may also be used to increase mixing. A typical design will split the stream and cause it to impinge at 180°, then continue on to the mold.

• A comparison of the materials shows the advantages over a similar injection molded material.

parameter	RIM (Thermoset Urethane)	Injection Molding (Thermoplastic Urethane)	Injection Molding (Glass-filled EPDM)
tools			
construction	Nickel electroform; machined aluminum	Machined steel	Machined steel
weight, lb	1,300	13,000	13,000
weight, kg	600,	6,000	6,000
cost, $	60,000	125,000	125,000
lead time	20 weeks	28 weeks	28 weeks
equipment			
molding machine weight, lb	10,000	120,000	120,000
molding machine weight, kg	4,500	54,000	54,000
cost of material and mold handling equipment per molding station	$60,000	$300,000	$300,000
floor space required, sq. ft.	70	400	400

Material:	Urethane	EPDM, glass-filled
process:	RIM	Thermoset injection molding
nominal thickness, in.	0.120	0.120
specific gravity	0.95	1.25
weight per sq.ft., lb	0.59	0.78
raw material cost/lb	$0.60	$0.55
raw material cost/sq.ft.	$0.35	$0.43
process factors		
cycle time, min	3.0	3.0
press capacity, tons	100	3000
floor space required, sq.ft.	100	500
paintability	Excellent	fair

EPDM = Ethylene propylene

46.1.1 References

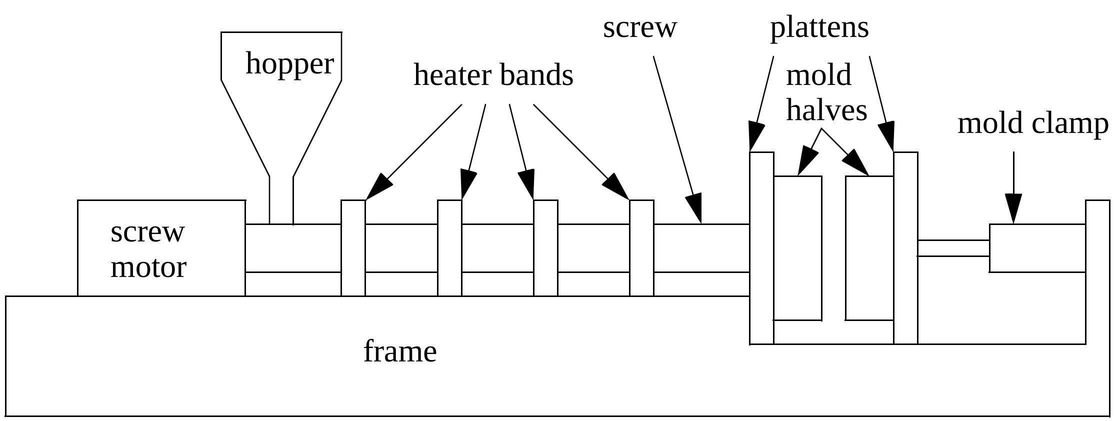
Becker, W. E., editor, Reaction Injection Molding, Van Nostrand Reinhold Co., New York, 1979.

46.2 INJECTION MOLDING

• Basic process - Heat a thermoplastic material until it melts. Force it into a hollow (cooled) cavity under pressure to fill the mold. When cool remove the finished part.

• Typical materials are,
  - nylon
  - styrene
  - ethylene

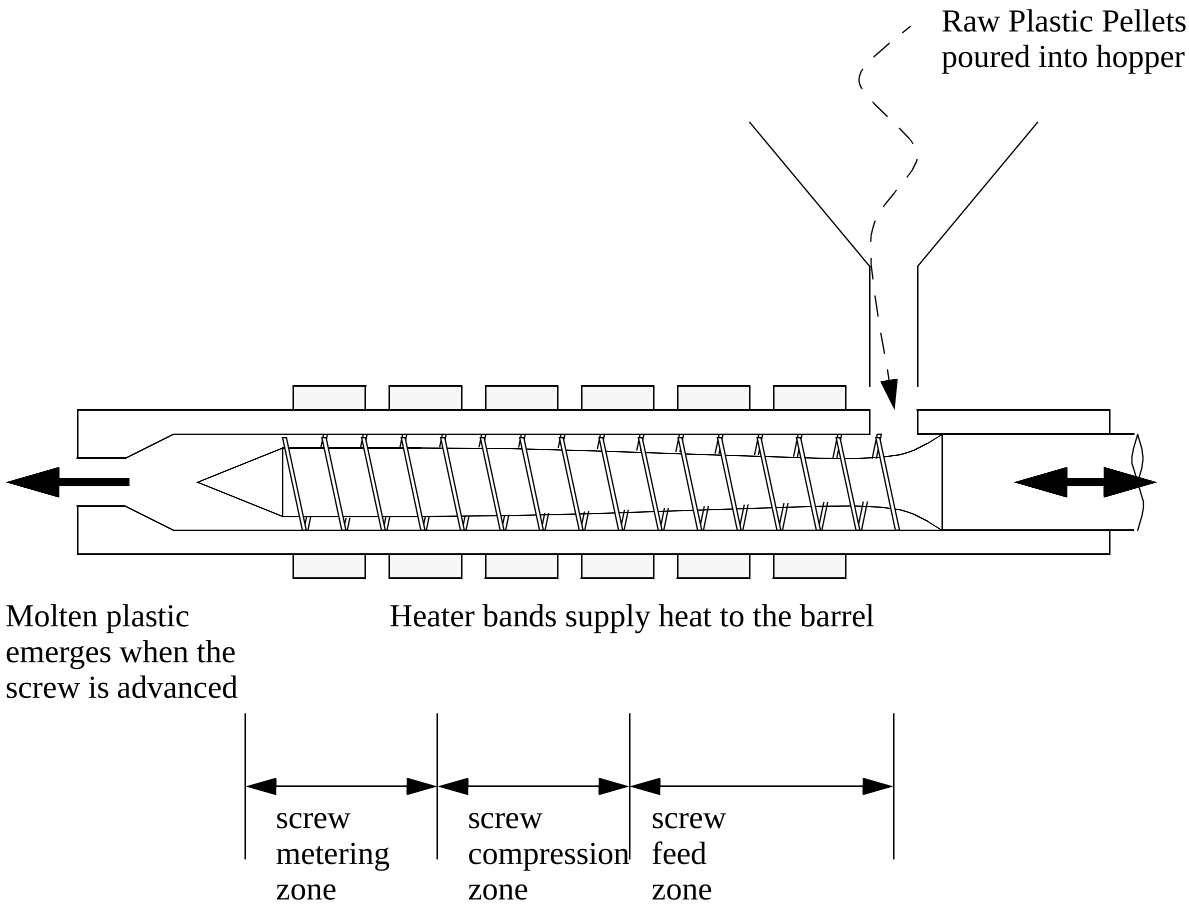
• A typical injection moulding machine is seen below with the covers removed. Plastic pellets are poured in the hopper, and finished parts emerge from the dies.



• Injection system,
  - a material hopper acts as an input buffer
  - a heated chamber melts the material
  - an injector forces the now viscous fluid into the mold

• Previous mechanisms used an injection plunger.

• Current mechanisms use a reciprocating screw,
  - basically the screw extends from the hopper to the injection chamber.
  - along the length of the screw chamber, heater bands are used to melt the plastic.
  - as the screw turns, it moves raw solid plastic from the hopper, to the injection chamber. The buildup of pressure in the injection chamber forces the screw back until enough for a shot has accumulated.
  - the screw is forced forward to inject the plastic into the mold.



- there is a contribution to melting by pressure that allows the temperature of the heating bands to be lower.
- the purpose of the screw is to generate a homogenous melt with little orientation in flow direction.

• Typical zones can be identified on the screw,
  - feed - a screw with large cavities to carry more material.
  - compression - the depths of the screw thread reduce, leading to elevated pressures, and pressure induced melting.
  - metering - small and uniform threads to provide controlled quantities. This also serves as a final mixing stage.

• Screws are often low/medium/high compression ratio as a result of the change of screw volume from the feed to the metering stages - screw selection will vary between materials, but a low compression ration screw will ensure good melting in most cases.

• Screws are nitride treated to improve tool life. Screws might also be made slightly smaller to compensate for thermal expansion when heated.

• Screws are often driven by electric or hydraulic motors.

• The heat capacity and melting point temperatures of various materials determine the energy required to melt the plastic and the energy to be removed for solidification (and for ejection).

• The volume of the injection chamber determines the maximum mold cavity size. The volume provided is often for polystyrene. When using other materials the volume can be corrected using the following formula. For example a 10 oz. shot,

$$\left(\frac{SG_{material}}{SG_{polystyrene}}\right)(oz_{shot}) = \left(\frac{SG_{material}}{1.05}\right)(oz_{shot})$$

• The mold is held closed with a certain clamp tonnage.

• As cycle times decrease, the plastic melt becomes less consistent.

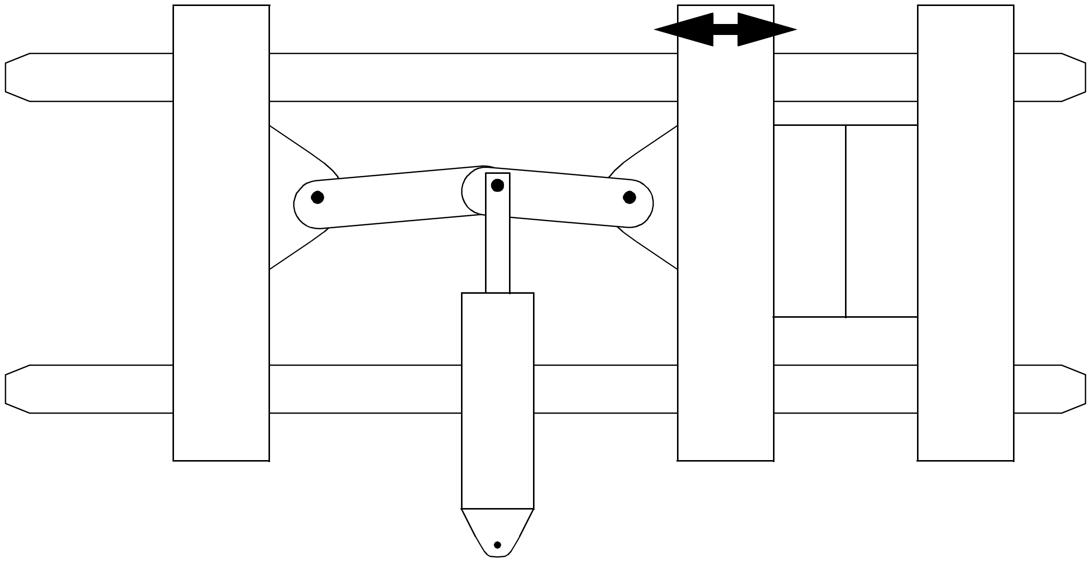
• Each heating zone uses electrical heating bands with thermocouples, or pyrometers to control the temperature.

• When injecting, the mold is moved then clamped shut. The mold halves are mounted/clamped/screwed on two platens, one fixed, one moving. The stationary platen has a locating ring to allow positioning on the mold half over the injection nozzle. The moving half has ejector pins to knock out the finished part. Larger plates are found on larger injection molding machines.

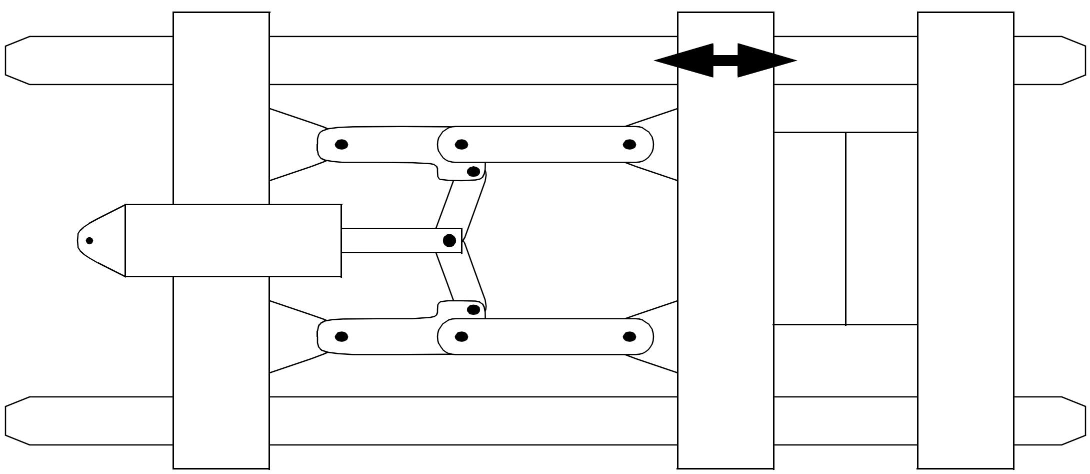
• Injection molding machines pressure is calculated as injection pressure over an area in the mold. Consider the case where a mold with a 10 square inch mold is being filled in a 200 ton machine.

$$P = \frac{F}{A} = \frac{200}{10} = 20\frac{tons}{inch^2} = 40ksi$$

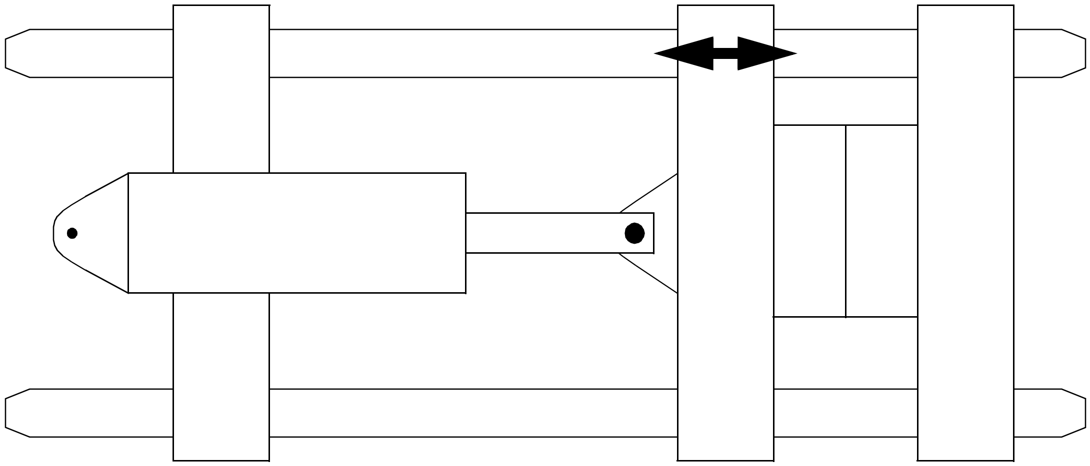
• The platens are actuated by hydraulic driven mechanisms. These are slow, but can exert great forces. In lighter presses other mechanisms can be used.



A single toggle clamped mechanism shown in the locked position



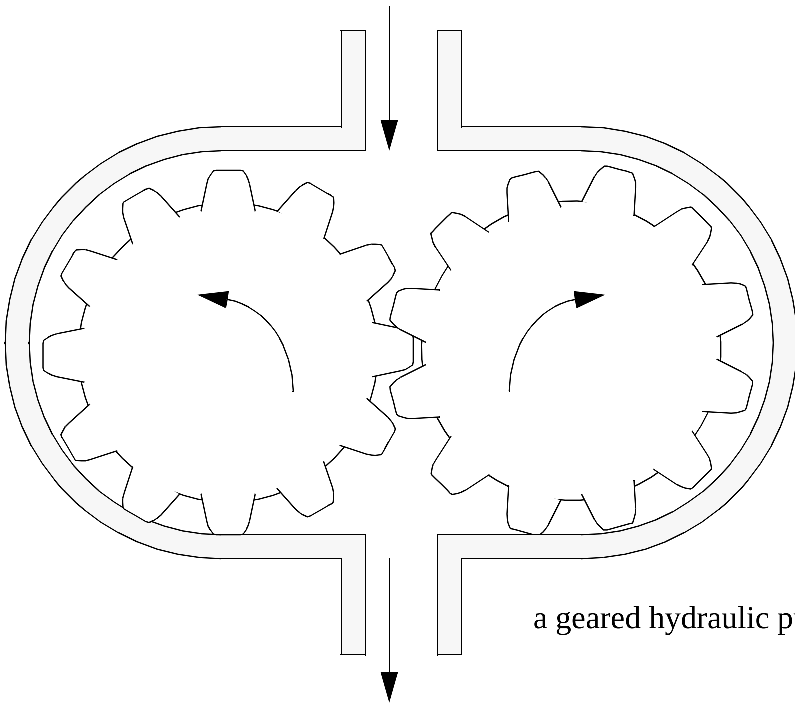
A double toggle clamp in the locked position



A Basic hydraulic clamp system

46.2.1 Hydraulic Pumps/Systems

• A geared hydraulic pump is pictured below. Other types use vanes and pistons.



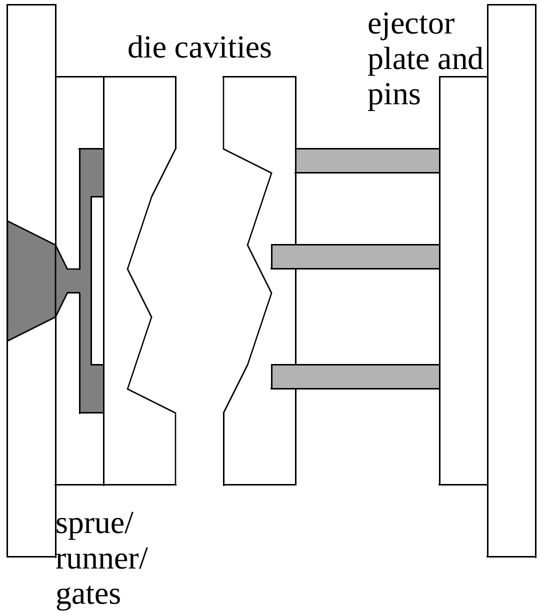
a geared hydraulic pump

• Hydraulic systems use pumps to cause fluid flow. Resistance to that flow will allow pressure to build up. This fluid is directed through a systems with,
  - oil filters to clean
  - heat exchangers to cool oil
  - gages to monitor pressure
  - relief valves to release fluid when a maximum pressure is passed
  - a reservoir to collect uncompressed fluid
  - check and flow valves

• The hydraulic system drives pistons and other hydraulic actuators.

46.2.2 Molds

• Injection molds are mainly made of steels and alloys steels. A simple mold is shown below.

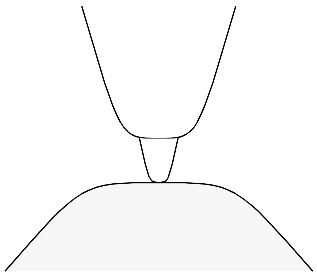


Locating ring - guides the injection nozzle into the mold.
Sprue Bushing - where the injected material enters the mold cavities.
Clamp front plate - Secures the front cavity, locating ring, and other components to the stationary platen.
Front cavity - holds half of the negative of the shape to be molded. Guide pin holes are put in this plate.
Rear cavity - the mating half for the front cavity that completes the negative of the final part. Guide pins are mounted on this to ensure correctly aligned cavities.
Spacer Blocks/Rails - used to separate the rear cavity from the rear clamp plate.
Ejector housing - contains the ejector pins to knock the parts out of the mold and forces the cavity back when the mold is closed.
Rear Clamp Plate - Supports the rear half of the mold on the moving platen, and provides rigidity under molding pressures.

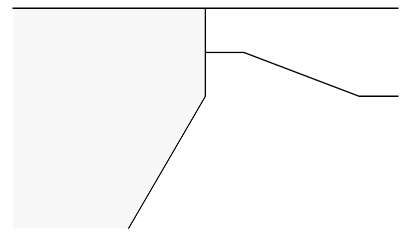
• Components to consider in mold design,
- part design
- material
- machine used

• Factors that are often altered in the design are,
- gating
- runners
- mold cooling
- ejection

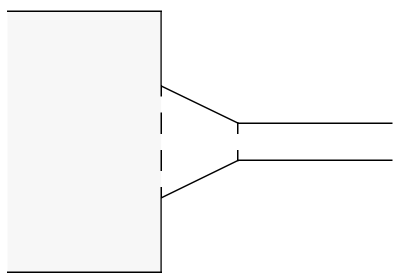
• Gating can be done a number of ways



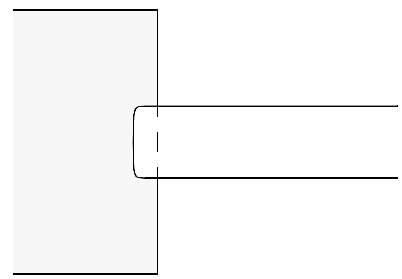
Center Gate



Edge Gate



Fan Gate



Tab Gate

• Runners carry the plastic to the injection gates and are often considered disposable or reusable. Typical runner systems are,
  - cold runner
  - hot runner
  - insulated runner

• Cooling systems allow rapid uniform cooling to increase cycle times, and reduce scrap. Typical techniques are,
  - water lines
  - baffles
  - fountains
  - thermal pins

• Ejection systems will push the part out of the mold when it is opened.
  - knockout pins
  - blades
  - stripper rings
  - air
  - hard stripping

46.2.3 Materials

• Materials often come as raw beads. These can be mixed, colored, have other materials added, or reused.

• Quite often scrap parts are ground up, mixed with new materials and reused. But, caution is required to reduce contamination.

• Common materials are,

Material	Example Applications	Properties
Acetals	gears, bearings	tough, natural to opaque white
Acrylics	lenses, reflectors	similar to wood strength, transparent
A.B.S.	appliance housings	tough, opaque
Cellulose Acetate	glass frames	flexible to rigid, tough, transparent
Nylon	bushes and bearings	very tough, almost opaque
Polycarbonate	safety helmets	tough and resilient, transparent
Polyethylenes - low density	kitchen containers	tough and flexible, waxy look
Polyethylenes - high density	milk crates	tough and stiff, waxy look
Polypropylenes	shovel handles	tough and stiff, waxy look
Polystyrenes - general	cosmetic containers	brittle, transparent
Polystyrene - high impact	plastic model toys	tough, translucent
PVC - rigid	pipes	tough, transparent or opaque
PVC - plasticized	kitchen flooring	tough and flexible, transparent or opaque
SAN	disposable cutlery	brittle, transparent

46.2.4 Glossary

Barrel - the cylinder the injection screw sits in.
Cavity/Impression - The two or more hollow metal parts that contain the negative of the part.
Cold Flow - material that is too cool when injected will get a dull surface finish.
Core - a protruding (or male) mold component.
Crazing - a fine mesh of cracks.

Degating - separate parts from runners
Delamination - the surface peels off in layers
Dowels/Guidepins - used to mate mold cavities
Distortion - a warped molding
Dwell - a delay time after filling the mold
Ejector Pins - push the part out of the mold as it is opened
Feed - the volume of plastic injected into the mold as it is advanced
Flash - a thin flat section that has “squirted” out of the mold
Gassing - trapped gas marks and burns the mold
Gates - the entry port between the runners and the parts
Granules - the pellet form that raw plastic is delivered in.
Granulation/Grinder - will reduce parts to granules for reuse
Inserts - parts placed in the mold before closure and injection. These become an embedded part of the final product
Nozzle - the plastic is ejected through the nozzle to the mold.
Polymers - The chemical category of plastics
Powder - a finely ground material
Preheating - plastic may be heated before use to remove moisture contaminants
Purging - a few purging shots are made when changing the material
Ram - opens and closes the platens
Regrind - reclaimed plastic granules
Release Agent/Spray - A spray, such as silicone, can be sprayed into tight molds to ease part removal.
Runners - connect the gate to the sprue
Safety gate - the gate must close and shut the operator out for the press to close.
Shot - one injection of plastic
Short shot - insufficient plastic is injected
Shrinkage - reduction in size as mold cools
Sinking - Surface deformation on parts.
Sprue - excess plastic between the injector nozzle and the mold
Vent - A small gap that allows air to escape as it is displaced by molten plastic
Warped - Cooling stresses cause a part to twist, or warp, to a new shape.

46.3 EXTRUSION

• The basic process - plastic is melted and pushed through an extrusion die with a desired cross section. The plastic leaves the die in roughly the right shape. It is then passed through a sizing and cooling apparatus. Finally, for wound product, it passes through pullers, and onto a spool.

• Basically a screw, like that described in injection molding is used to melt the plastic and generate pressures.

• Some additive for plastics are,

- white chalk, used as a filler
- plasticizers, improve flexibility
- stabilizers, improve light and heat resistance
- pigments
- lubricants minimize sticking and improve flow

• Typical extrusion conditions are, [Source, unknown]

Applic. /Material	Extruder (h.p.)	extruder barrel (in.)	Barrel Rear Temp. (°C)	Barrel Front Temp. (°C)	Die Temp. (°C)	Typical press. (atm.)	Typical Material Temp. (°C)	Typical Takeoff Conditions
Pipe								
Polyethylene	40	3.5	150	160	165	100	165	Room temp. water cooling
Rigid PVC	50	3.5	140	160	170	175	175	Room temp. water cooling
ABS	50	3.5	170	195	200	175	200	room temp. water cooling
Sheet								
Polystyrene	100	4.5	180	200	210	70	210	rolls
Linear Polyethy.	100	4.5	230	205	200	175	220	rolls
Film								
Tubular Polyeth.	40	3.5	150	160	165	100	165	blow up 2:1
Flat Polyethy.	40	3.5	200	240	250	65	250	chilled roll
Rigid PVC	25	2.5	140	160	170	150	175	horiz. tubular bubble
platicized PVC	50	3.5	140	170	175	100	180	vert bubble, blowup 2.5:1
Coating								
Polyethylene	100	4.5	250	315	325	75	320	substrate 100°C, roll 50°C
Wire								
Polyethylene	50	3.5	220	240	240	200	240	preheat 150 bath70,40,15°C
Plasticized PVC	25	2.5	130	165	170	100	170	preheat 150, bath 20°C
Nylon	15	2	260	295	300	60	300	preheat 150, bath 70, 20°C
Monofilaments								
Polypropylene	25	2.5	190	240	250		250	quench 50, air oven 200°C
Nylon	25	2.5	260	290	300		300	Quench 90, oven 260°C
Polystyrene	20	2.5	180	205	210	100	210	glycol bath 125°C
Contours								
Polystyrene	20	2.5	175	200	205	100	200	flame polish 400°C or cool
Rigid PVC	25	2.5	140	165	170	175	170	tap water in vacuum sleeve
Platicized PVC	20	2.5	140	165	165	75	165	Flame polish 400°C, bath

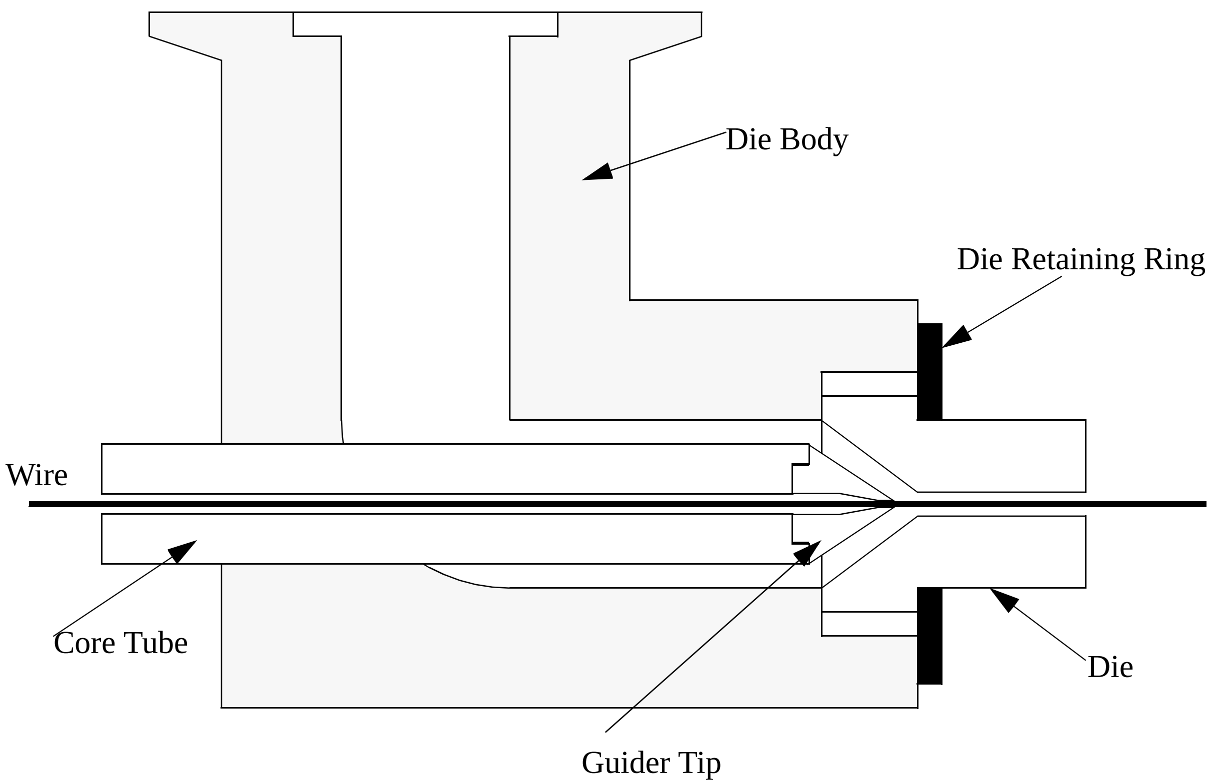
• The typical extruder barrel is between 20:1 and 28:1 for length to dia., and typical pressures are 10 to 20 ksi.

• Typical motor characteristics are,
  - 5 to 10 lbs of material per hour for each horsepower
  - the motor is geared down to drive the screw (often variable)

• Breaker plate,
  - at end of screw, and before extrusion die,
  - it increases back pressure for the screw

- converts rotational to parallel flow
- it stops unmelted plastic and debris

• Special heads can be used to coats wires, etc.



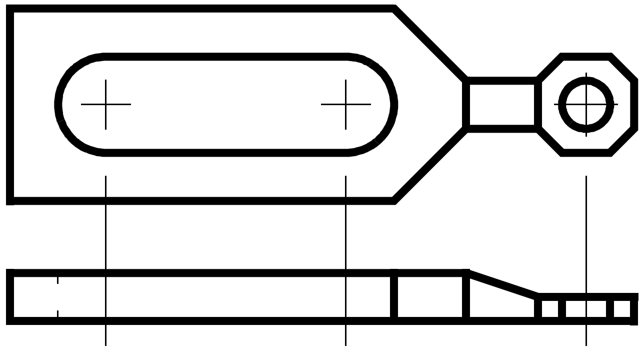
46.4 PRACTICE PROBLEMS

1. TRUE / FALSE - Plastic is melted in the hopper before it is extruded.

2. TRUE / FALSE - A reciprocating injection moulding process has a screw that moves.

3. TRUE / FALSE - Steam is the most common method used to weld plastics.

4. The key tag shown below has a flat profile. There is a hole on the right hand side for the key-ring, and a large hole in the main body of the ring.



a) Design and sketch a complete injection mold for the part. Indicate parting lines, ejector pins, runners, gates, and all other important features.
b) What important design features must be considered for a part like this?

5. List 5 tradeoffs injection molding and reaction injection molding?

6. Describe the operation of an injection molding machine using figures and notes. This should describe the entire cycle from when plastic enters the hopper to when it is injected into the part.

7. Name the three zones on a plastic compression screw and briefly describe the function of each zone.

8. List the general advantages of thermo plastics over metals. List the disadvantages.

9. A six cavity mold has been designed for a 200 ton injection molding press. The press is no longer available, and the mold has to be put in a 160 ton press. How many cavities should be blocked off to ensure the mold will fill properly?

10. a) Describe the operation of the screw in an injection molding machine.
b) How would the operation of the screw change for a continuous extrusion machine?
c) What does the tonnage of an injection molding press refer to?
d) What types of cooling channels can be used inside an injection mold. Describe how they operate.

11. Why do powder metal parts change shape after processing? What can be done about it?

12. What are the advantages of injection molding over other processes.

13. What is the purpose of gates in an injection mold? What are the different types, and what are their advantages?

14. What are parting and flow lines?

15.

47. ROLLING AND BENDING

• The basic process is,

1. We start with raw material in some form, typically there is one long dimension. The material may be hot or cold.
2. The material is then fed in between rollers.
3. The rollers apply a force to the material to thin or reshape the original cross section.
4. The material emerges from the other side of the rollers in a new shape.
5. The material may then be taken off, passed through another set of rollers, coated with oils, drawn, etc.

• There are two types of rolling,

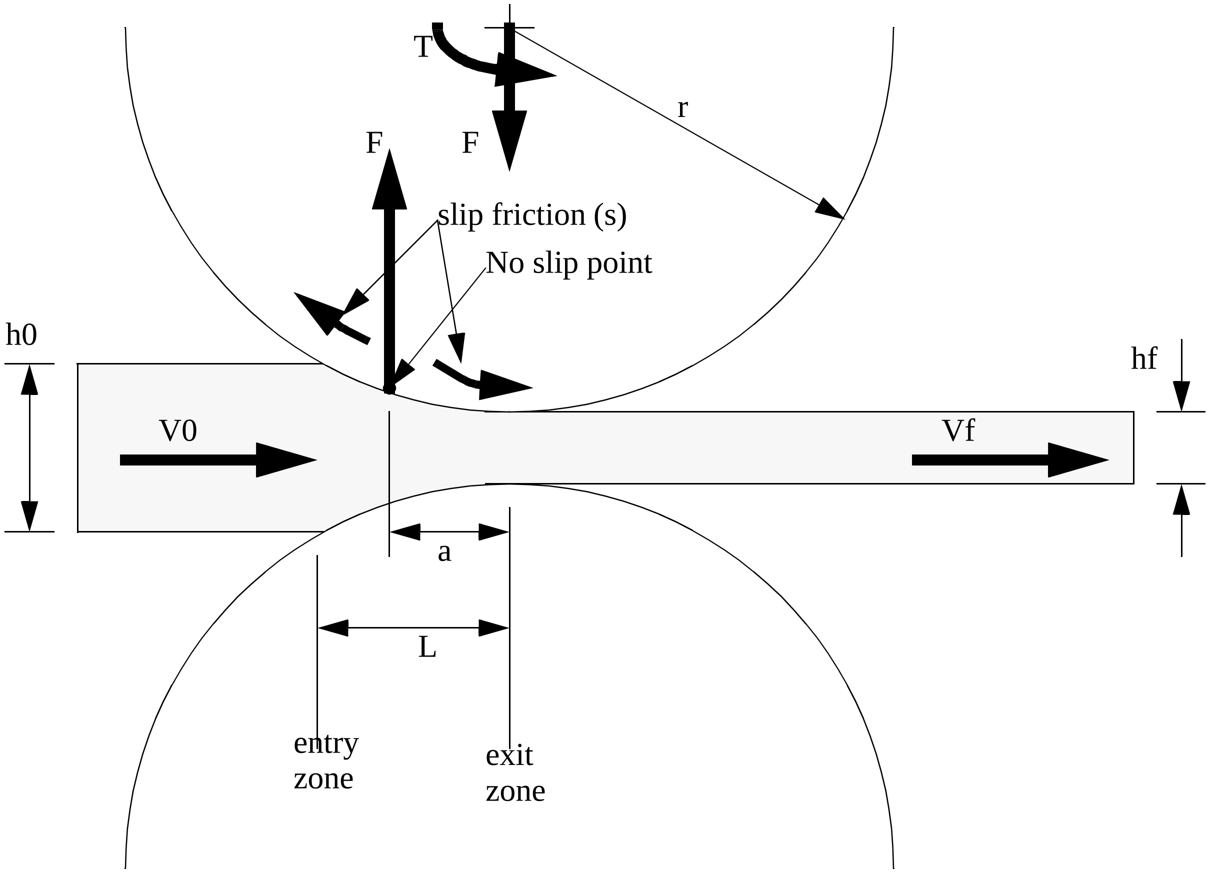
flat rolling - reduces the thickness of a sheet of material.
shape rolling - produces new parts with a complex cross section.

• Materials that have been rolled typically have a wrought structure with the grains broken down.

• Rollers play a large part in continuous casting after the molten metal is poured off into a bloom, or some equivalent form.

47.1 BASIC THEORY

• While the rollers are in contact with the work there is friction and force applied. There is typically slip between rollers and the work, but this slip is not constant over the surface of contact. The figure below illustrates the forces acting on a roller.



where,

a = distance to no slip point from exit zone (assume a=l/2)
F = Force applied to rollers
T = Torque applied to rollers
L = Roll gap
V0,Vf = sheet velocity before/after rolling
r = radius of rollers
h0, hf = before and after thicknesses of the sheet
w0, wf= with of strip before and after rolling
Yavg = average true stress of the sheet in the gap (assume between no slip points)
RPM = angular velocity of the rollers
P = power required to roll the sheet

$$h_0 - h_f = \mu^2 r \qquad \text{Maximum draft}$$

$$P = (force)(velocity) = (LwY_{avg})(RPM2\pi r)$$

47.2 SHEET ROLLING

- While rolling a sheet the rollers will be under significant forces. This will lead to deflections at the centers of the rollers. To overcome this rollers are made with a slight barrel shape. therefore when rolling the deformed rollers will take the desired shape.

- When rolling sheets have a tendency to spread. This means that the width of the sheet increases when it is rolled.

- Input and output materials in rolling are,
  - Sheets - up to 1/4” thick
  - Plates - between 1/4” to 12” thick
  - Billet - a square cross section of 6” or less per side
  - Bloom - a square cross section of 6” or more per side
  - Rods
  - Bars
  - Beams

- When rolling the material may be processed the following ways,
  - hot rolling is done above the recrystallization temperature (850°F for Al, and 1250°F for steel) and results in a fine grained wrought structure. The surface quality (500-1000 micro in.) and final dimensions are less accurate.
  - cold rolling is done near room temperature and produces better surface finishes (32-125 micro in.) and dimensional accuracy (0.004”-0.014”), but with strain hardening.
  - pack rolling involves rolling multiple sheets of material at once, such as aluminum foil.

- Defects in flat rolling include,
  - waviness
  - tearing on the sides (edge), or in the middle (zipper), or between the top and bottom faces (alligatoring)
  - spalling is cracking or flaking of surface layers results when improper material used in hot rolling
  - heat checking is cracking caused by thermal cycling this results when improper material used in hot rolling

- Residual stresses are also built up in rolled materials. The two possible variations are,
  - tension outside, compression inside - the result of large rollers, or high reductions
  - compression outside, tension inside - the result of small rollers or small reductions per pass

- In commercial rolling mills some techniques are used,
  - two-high, three high, four-high, cluster mills - multiple rollers can be used to increase the stiffness of the contact rollers.
  - tandem rolling - a number of rollers are used in series. Each point reduces the material thickness a step.

lubricants - used with cold rolling
coolants - used with hot rolling to cool the rolls and break up scale

47.3 SHAPE ROLLING

• In sheet rolling we are only attempting to reduce the cross section thickness of a material. If instead we selectively reduced the thickness we could form complex section easily. This technique is called shape rolling.

• In practice we can make complex cross sections by rolling materials in multiple passes. We can't do this in one pass because we would overwork the material, and it would crack.

• Some of the types of shape rolling are listed below,
ring rolling - a ring shaped part is rolled between two rollers.
thread rolling - a round shaft is placed between two flat surfaces having flattened screw thread projections. The surfaces are compressed and moved tangentially to produce threads on the shaft.
cross section - a billet or bloom is passed through a set of rollers that slowly transform it to the final shape.

• We may also use rolling to make seamless tube with the Mannesmann process,
1. A bar (cylinder) is rolled radially between two rollers.
2. The force applied by the rollers creates a stress concentration at the center of the bar which may or may not lead to a central crack in the bar.
3. A mandrel is forced into the center where it pierces the hole, and ensures a desired size.
4. The rollers are oriented so that they slowly pass the bar through and onto the mandrel.
5. The finished tube is removed from the mandrel.

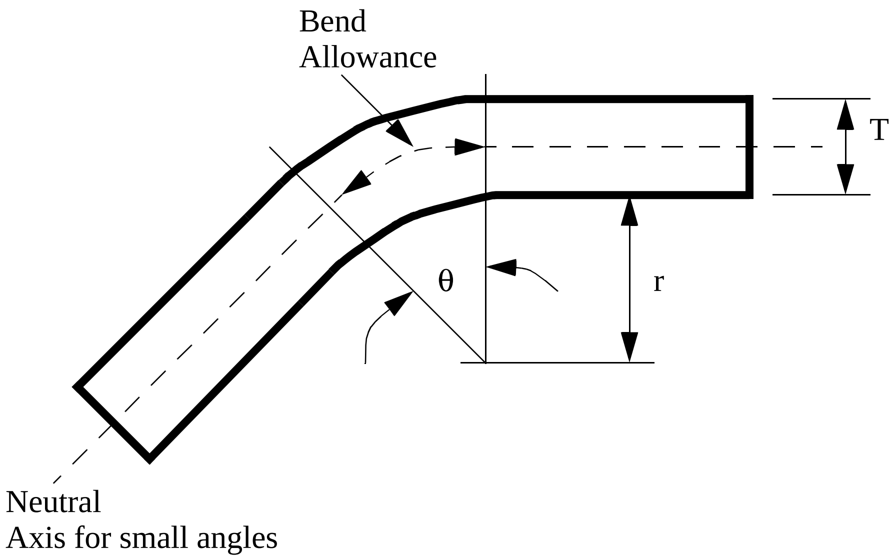
47.4 BENDING

• After basic shearing operation, we can bend a part to give it some shape.

• Bending parts depends upon material properties at the location of the bend.

• Some of the things that may/do occur in bends,
- material at the outer bend radius undergoes tensile plastic deformation
- material at the inner bend radius undergoes compressive plastic deformation
- the width (along the bend axis) will reduce in length based on poissons ratio
- if the bend radius is too small the plastic deformation at the outside of the bend will result in fracture.

• The basic calculations for a bend radius are shown below,



$$L_b = \theta(r + kT)$$

where,

Lb = bend allowance
r = bend radius to neutral axis
k = constant for material
T = thickness of material
theta = bend angle

r	k
<2T	0.33
>2T	0.5

• The strain on the outermost fibers of the bend is,

$$\varepsilon = \frac{1}{\frac{2r}{T} + 1}$$

Based on this equation, and various material properties, we can suggest minimum radii for various materials.

Material	Soft	Hard
Aluminum Alloys	0	6T
Beryllium Copper	0	4T
Brass, low-leaded	0	2T
Magnesium	5T	13T
Steel - Austenitic Stainless	0.5T	6T
Steel - Low Carbon	0.5T	4T
Steel - Low Alloy	0.5T	4T
Titanium	0.7T	3T
Titanium Alloys	2.6T	4T

• After sheet metal is bent it will tend to spring back to a lesser angle. The following formula relates bend radius before and after release.

$$\frac{r_{before}}{r_{after}} = 4\left(\frac{r_{before}\sigma_{yield}}{ET}\right)^3 - 3\left(\frac{r_{before}\sigma_{yield}}{ET}\right) + 1$$

• There are a variety of methods for springback compensating,
 - trail and error to over bend
 - calculated over bend
 - special punch/die designs

• The maximum bending forces may be calculated using the relationship below,

$$P = \frac{k\sigma_{yield}LT^2}{W} = \frac{\sigma_{UTS}LT^2}{W}$$

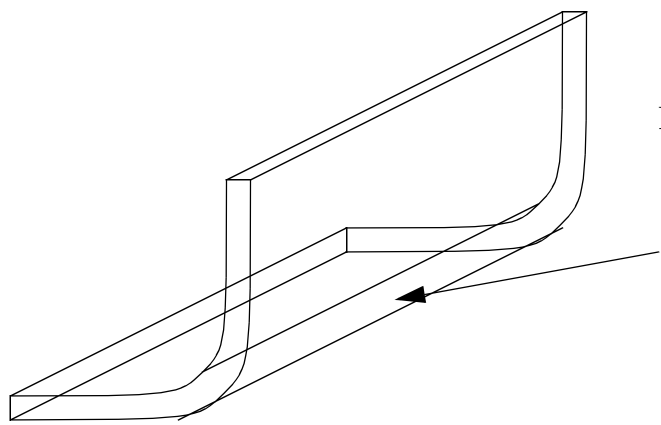
where,

P = the maximum bending load
W = the distance between reaction supports
L = length of bend (along bend axis)
k = constant for particular dies from 0.3 to 0.7

• Press Brakes a small presses that will bend a sheet metal piece over several feet.

• Some other operations done to sheet metal parts,
beading - the edges of the sheet metal are bent back (in a rounded shape) to stiffen the edges and eliminate the sharp edge.
flanges - a hole can be formed by punching through, and a lip (the flange) remains about the edge of the hole
Hemming - like a bead, but the edge is bent back as a flat.
Roll Forming - Bends can be made along long axes by using rollers.

• When planning to bend a piece, car must be take not to punch holes too close to the bend.



holes or other features near the bend will become distorted or will not take the radius of the round (scalloping). Leave them a distance from the radius that is 3 to 5 times the metal thickness.

• Quality problems that occur in rolling are,
flatness
twist
straightness

48. SHEET METAL FABRICATION

• Sheet metal typically begins as sheets, but after undergoing cutting, bending, stamping and welding operations it takes on useful engineering forms.

• Sheet metal has become a significant material for,
- automotive bodies and frames,
- office furniture
- frames for home appliances
-

• Sheets are popular materials because the sheets themselves are easy to produce, and the subsequent operations can be performed easily. The major operations typically include,
bending - an angle is used to create non-parallel faces
punching/shearing/blanking - a major portion of the material is cut off by putting the material in shear.
forming -
spinning -
stamping -
embossing -

48.1 SHEET METAL PROPERTIES

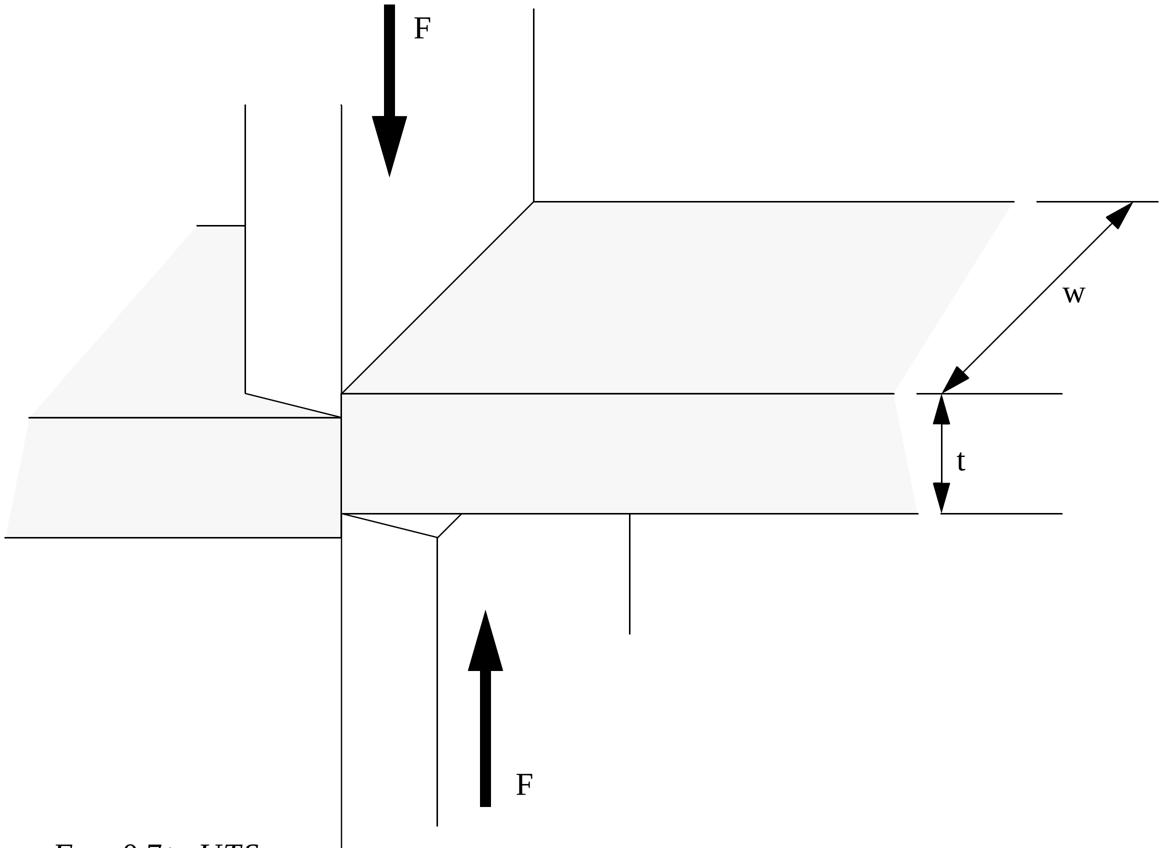
• The properties of sheet metal determine how well it can be stretched or bent.

• The various properties include,
- Formability - a larger strain rate exponent ‘n’ relates to longer deformation
- Uniform Necking - the higher the strain rate sensitivity ‘m’, the less localized the necking
- Uniform Elongation - when the yield point has upper and lower points the material may deform in bands - giving long depressions in work surface called Leuder’s bands. These may occur in low carbon steels and aluminum/magnesium alloys.
- Anisotropy - if the material properties have no directionality deformation will be even.
- Small Grains - finer grains are preferred for better metal properties and surface finish.

48.2 SHEARING

• A shear force is applied that will cut off part of a sheet. The cut off ‘blank’ becomes the workpiece.

• To find the shear force for a cut we can go back to the basic mechanics of materials (with one adjustment factor).



$$F = 0.7twUTS$$

where,

F = force needed to shear
t = thickness of sheet
w = width of sheet
UTS = Ultimate Shear Strength of material

• The basic terms used in shearing are,

Punching - a small section of material is sheared out of a larger piece and discarded.
Blanking - outside/surrounding material is cut off a smaller piece and discarded.
Die Cutting - small features are cut into the sheet, such as series of holes, notches (adjacent material removed), lancing out tabs (no material removed), parting to cut the sheet into smaller pieces.
Fine Blanking - dies are designed that have small clearances and pressure pads that hold the material while it is sheared. The final result are blanks that have extremely close tolerances.
Slitting - moving rollers trace out complex paths during cutting (like a can opener).
Steel Rules - soft materials are cut with a steel strip shaped so that the edge is the pattern to be cut.
Nibbling - a single punch is moved up and down rapidly, each time cutting off a small

amount of material. This allows a simple die to cut complex slots.
Nesting - a sheet can be used more effectively (reduce scrap) if part patterns are closely packed in before shearing.

• Dies used in shearing typically have small clearances between the punch (moving part) and Die (non-moving backing). If this gap is too great the parts will have rough edges and excess shear force will be required. Clearances that are too small lead to premature wear. Typical design issues for clearances are given below,
- for softer materials the clearances are generally smaller
- thicker sheets require larger clearances
- typical clearance values range from 2-8% of sheet thickness
- extreme clearances range from 1-30% of sheet thickness

• Typical dies will come in a number of forms,
- bevel/double bevel/convex shear dies - these have an angle on the punch or die so that the shear starts at one point and then moves, much like cutting with scissors.
- compound dies - a die has multiple punches and dies that operate on the piece at the same time
- progressive dies - a single die contains a number of die slots. A part will stop at each die inside the progressive die before it is complete. This type of dies allows slow working of parts.
- transfer dies - a sequence of dies in one or more presses will operate on a piece - this is basically a scaled up progressive die.

48.2.1 Progressive and Transfer Dies

• These have dies with stations that will

48.2.2 DRAWING

• Material is pulled into the die.

48.3 DEEP DRAWING

• Commonly the process is,
1. A blank is clamped over a die so that it is not free to move.
2. A punch is advanced into the material, forcing it into the die and permanently deforming it.

3. The punch is removed, the part removed from the die, and the excess blank is trimmed off.

• Typical applications for this process include pots, cups, etc.

48.4 SPINNING

• Basically,
1. A mandrel (or die for internal pieces) is placed on a rotating axis (like a turning center).
2. A blank or tube is held to the face of the mandrel.
3. A roller is pushed against the material near the center of rotation, and slowly moved. outwards, pushing the blank against the mandrel.
4. the part conforms to the shape of the mandrel (with some springback).
5. The process is stopped, and the part is removed and trimmed.

• This process can form very large items well over 10’ in diameter.

• Items that can be produced are,
- buckets
- pots
- satellite dishes
- inlet rotated parts

48.5 MAGNETIC PULSE FORMING

• Basic operation,
1. A large current discharge is directed through a coil. The coil has been placed inside another shape.
2. The discharging current creates a magnetic field. In the nearby sheet of metal an opposing magnetic field is induced. The result is that the two magnetic fields oppose and a force moves the sheet away from the coil.
3. Over a period of time the part is deformed, often to the shape of a mandrel, or other form.

• Applications,
- fittings for ends of tubes
- embossing
- forming

• Capacitor banks are used to accumulate charge for larger discharges.

• The part is formed to a mandrel that has a negative image of the part.

• The method generates pressures up to 50 Kpsi creating velocities up to 900 fps, production rates can climb to 3 parts a second.

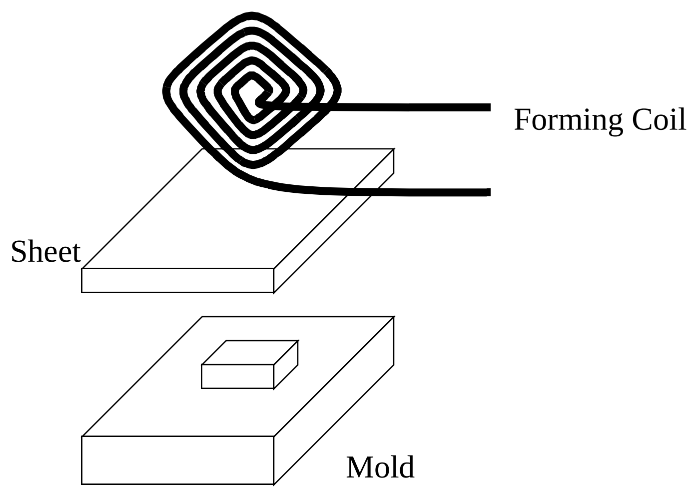
• Applications,
  - ball joint seals
  - fuel pumps
  - baseball bats

• Generally there are three methods of magnetic forming,
  - swaging
  - expanding
  - embossing and blanking

• Swaging - An external coil forces a metal tube down onto a base shape (tubular coil).

• Expanding - an inner tube is expanded outwards to take the shape of an outer collar (tubular coil).

• Embossing and Blanking - A part is forced into a mold or over another part (a flat coil) - This could be used to apply thin metal sheets to plastic parts.



• Advantages,
  - easy to control
  - allows forming of metals to any material
  - no contact eliminates many requirements such as lubricants, heat dissipation, surface repair, etc.
  - parts are uniform
  - no tool wear
  - minimal operator skill

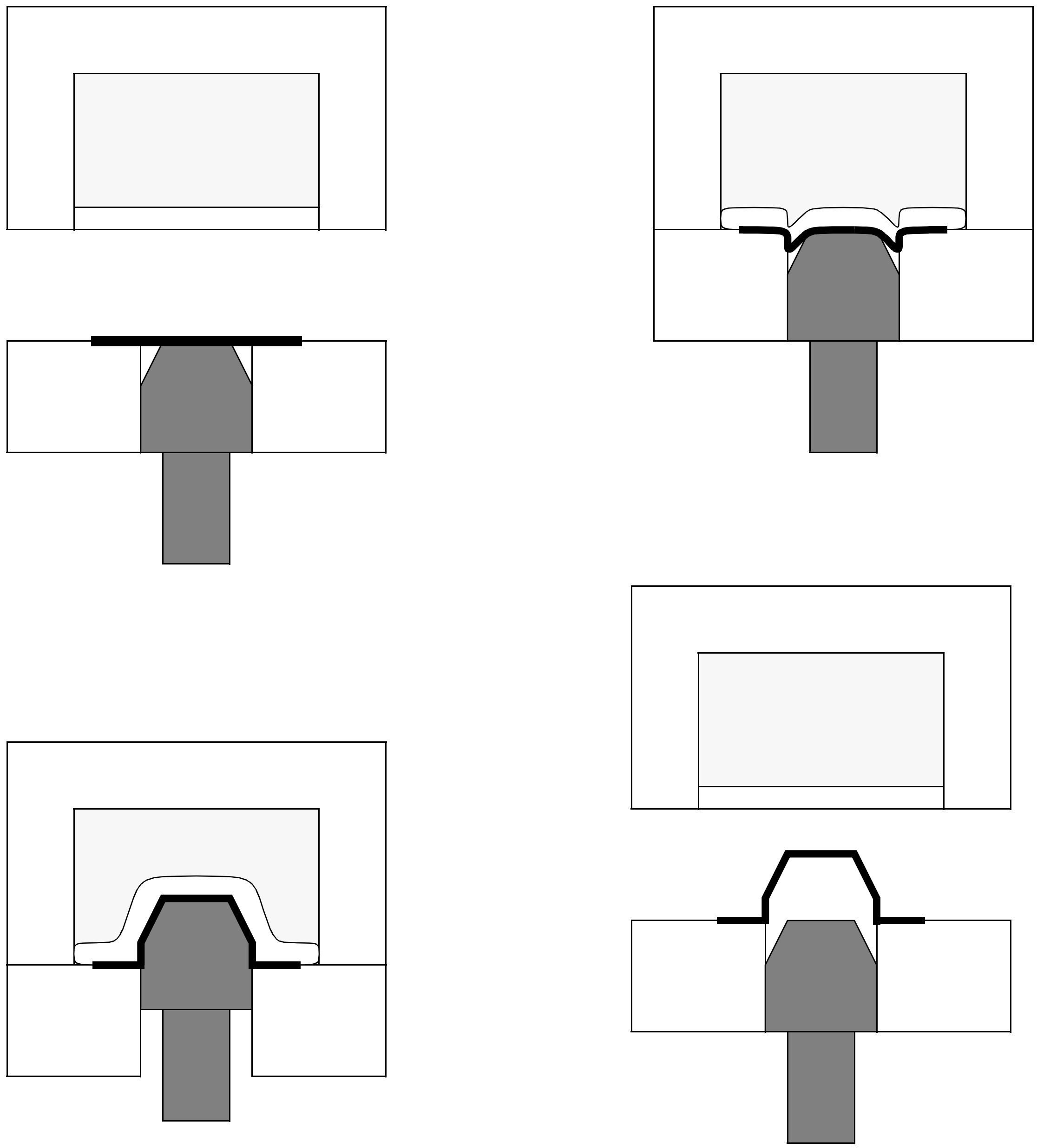
- very strong joints
- energy efficient
- easy installation
- high production rates (typically a few seconds)

• Disadvantages,
  - complex shapes not possible
  - no pressure variations over work
  - limits forming pressures

48.6 HYDROFORMING

• Basic process,
  - A metal sheet is placed over a male punch.
  - Fluid is on the other side of the metal sheet.
  - The punch advances and the metal sheet is forced into the shape of the punch. The hydraulic chamber acts as a mate for the punch.

• The basic operation is,
  1. The metal is placed between the fluid chamber and the punch bed.
  2. The fluid is encased behind a wear pad, and this wear pad is brought into contact with the sheet with pressures up to 5 Kpsi.
  3. The punch is advanced with pressures up to 15 Kpsi causing the metal to take the shape of the punch.
  4. The pressures are released, the punch withdrawn, the fluid chamber pulled back to remove the metal part.

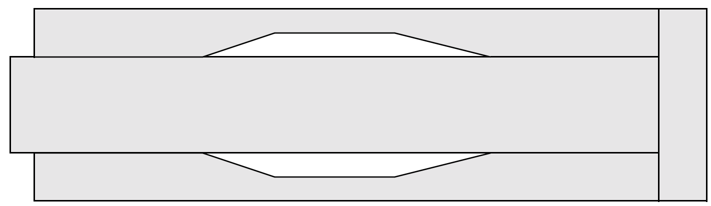


• Compared to conventional forming,
  - higher drawing ratios
  - reduced tool costs
  - less scarring of parts
  - asymmetrical parts made in on pass
  - many high strength alloys can be formed, for example stainless steel

• Compared to spinning,
  - faster forming speeds

- fewer anneals required
- only rotational parts possible with spinning

• Methods permissible,
- punch forming - for large drawing depths
- negative punch forming - allows recessed features
- cavity die forming
- male die forming
- expansion forming



• Advantages,
- any type of sheet material can be used
- thicknesses of 0.1 to 16mm
- tools can be used for more than 1 metal thickness
- flexible and easy to operate
- less expensive tooling
- tolerances down to 0.002”
- reduced setup times
- less thinning
- reduced die wear

• Disadvantages,
- sharp corners difficult to control
- high equipment cost
- no holes in surface
- incorrectly set pressures may lead to buckling and tearing for high pressures

• Design points
- the metal springback should be considered in design, or the size of the punch/die changed through trial and error experiments.
- a draft (taper) of 1-2° will prolong tool life.
- the minimum part radius should be 2-3 times the sheet thickness.

• Applications,
- cups/kitchenware

- autobody panels
- covers

48.7 SUPERPLASTIC FORMING

• Basic process - some alloys can be slowly stretched well beyond their normal limitations at elevated temperatures. This allows very deep forming methods to be used that would normally rupture parts.

• Some materials developed for super plastic forming are,
  - bismuth-tin (200% elongation)
  - zinc-aluminum
  - titanium (Ti-6Al-N)
  - aluminum (2004, 2419, 7475)
  - aluminum-lithium (2090, 2091, 8090)
  - stainless steel (2205 series)

• In general the alloys should have a grain size below 5-8 microns and be equip-axed. The grain size must not increase if kept at temperatures 90% of melting for a few hours.

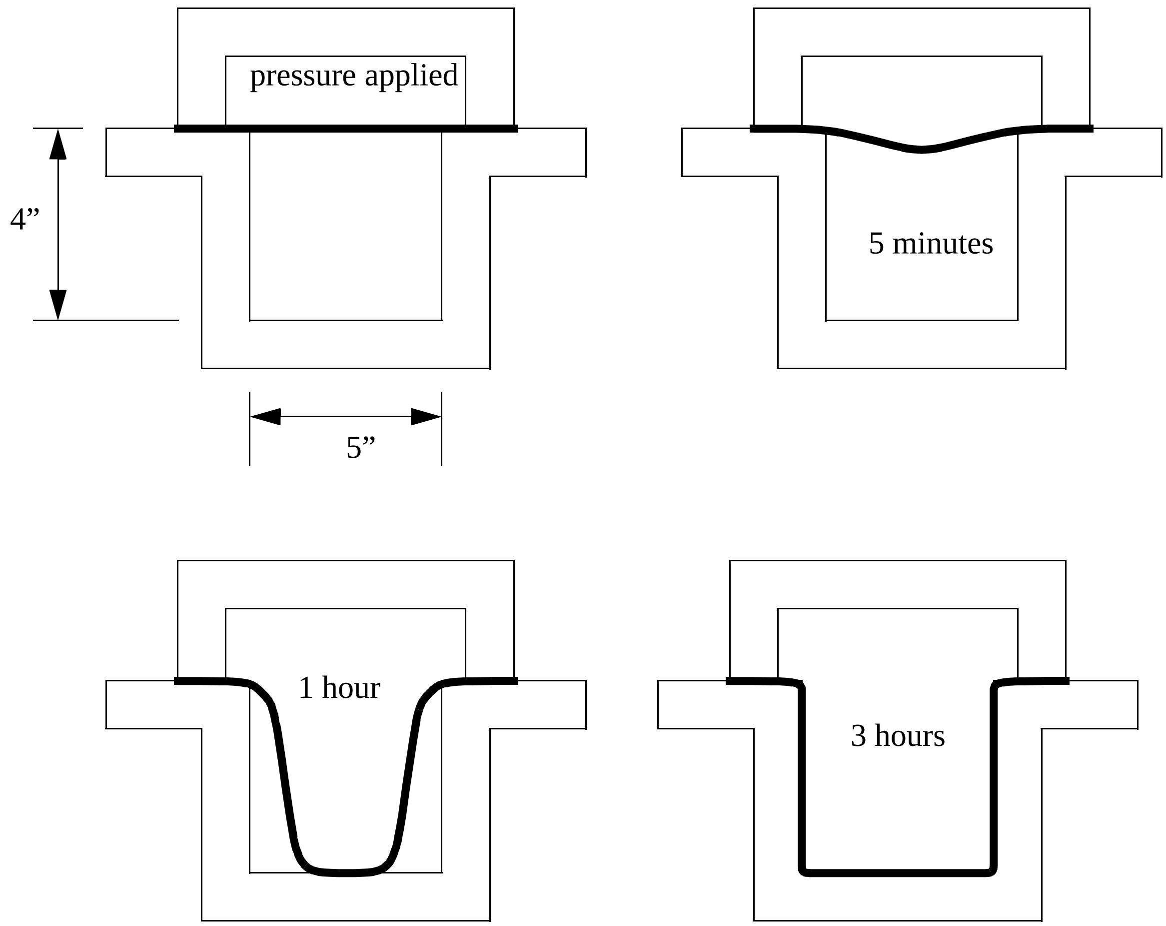
• Strain rates are generally low, approx. 10**-4/sec.

• Conventional forming techniques compared to SPF,
  - require multiple annealing and forming steps
  - have lower accuracy and repeatability
  - have springback
  - poorer surface finish

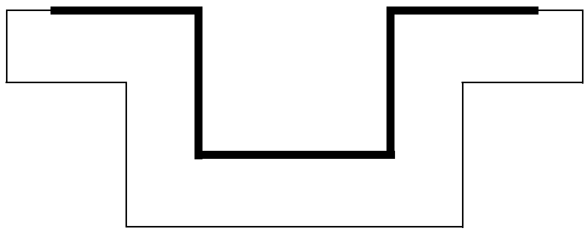
• For SPF of aluminum,
  - 70-90% of melting temperature
  - rate of 10**-4 to 10**-2 per second
  - typical time is 30-120 min.
  - temperature must be carefully maintained
  - cavitation (voids) can occur in the aluminum if pressure is not applied to both sides of the sheet - a different pressure still causes motion.

• Parts are less expensive because only half of the tooling is required.

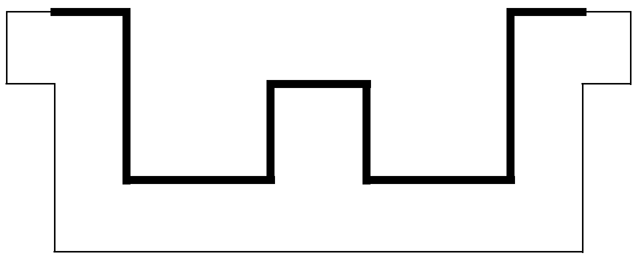
• The typical process is like,



• Various methods include,

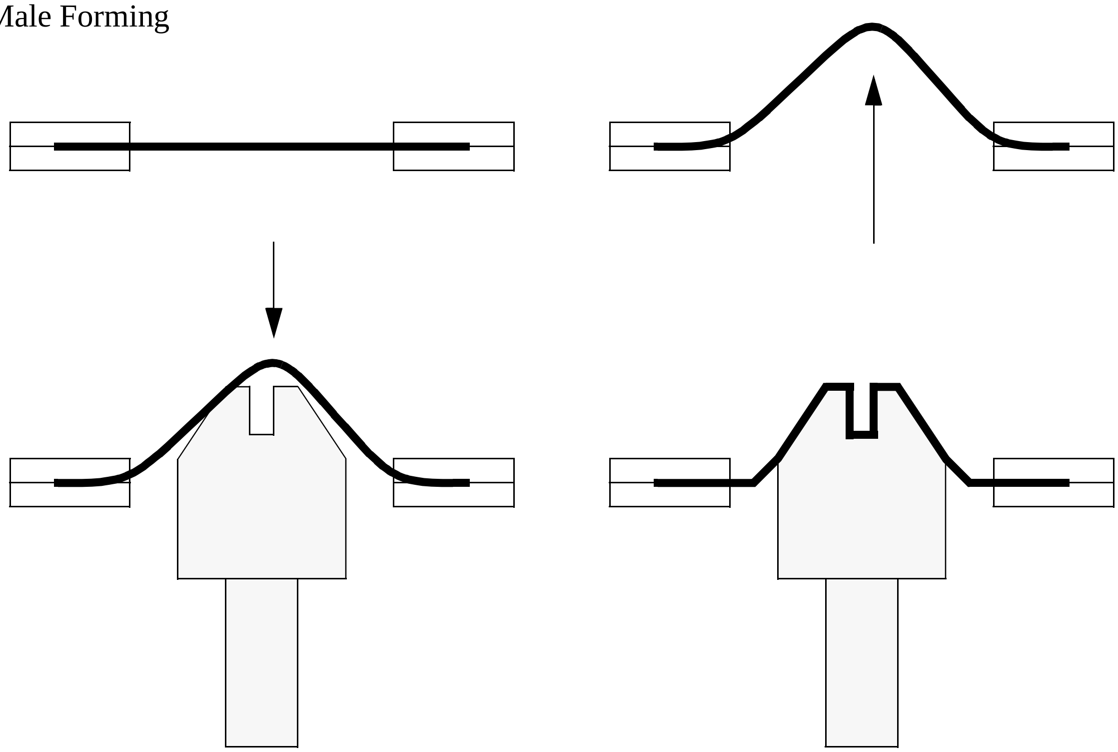


Female Forming



Drape Forming

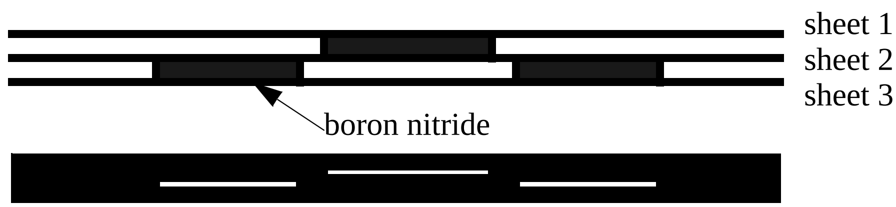
Male Forming



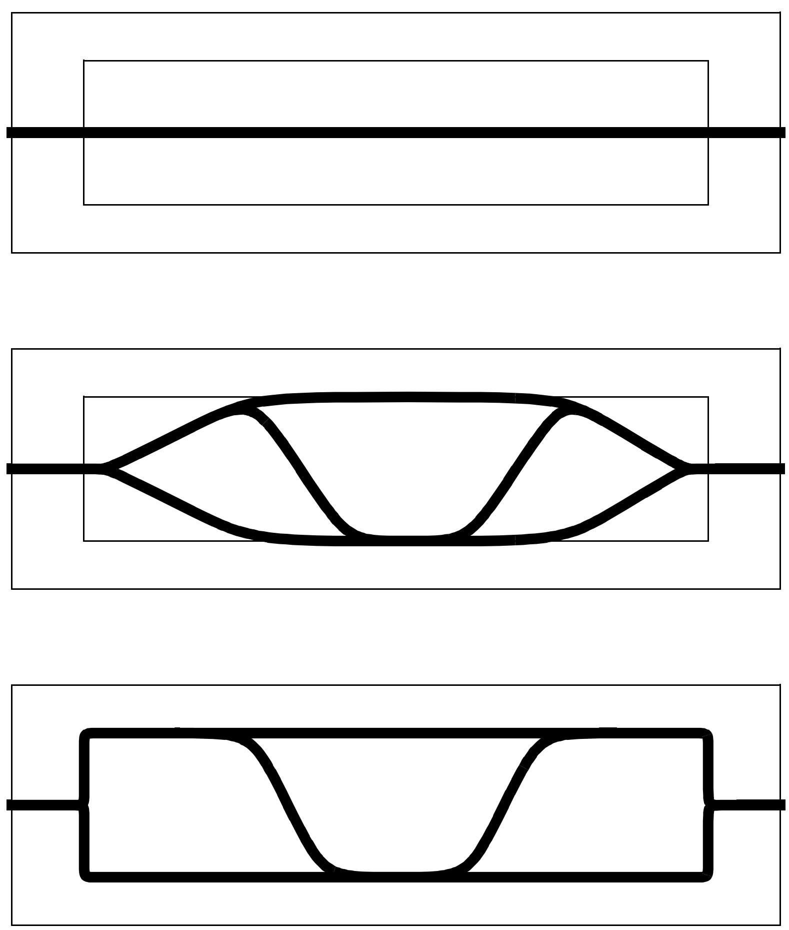
48.7.1 Diffusion Bonding

• Diffusion bonding is used with SPF to create more complicated shapes.

Step 1: The sheets have boron nitride placed on the sheets where no bonding is to occur. Sheets are put down in layers (with the boron nitride areas between), and heat and pressure are used to bond sheets together.



Step 2: the laminated sheets are put into a mold, and SPF is used to shape the outside. Pressure is applied by blowing air between the sheets. The boron nitride that stopped bonding before, now acts as a lubricant.

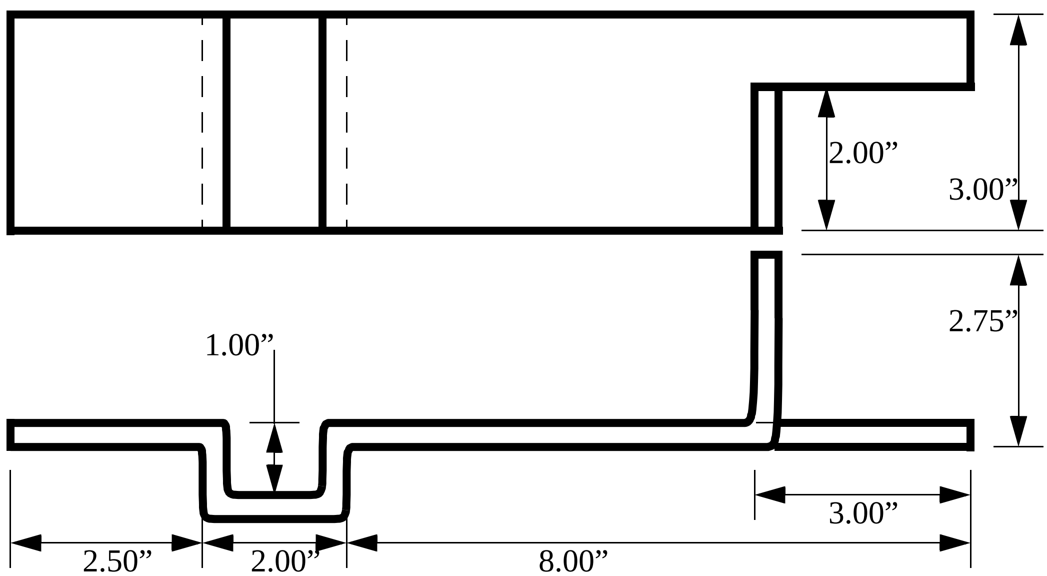


48.8 PRACTICE PROBLEMS

1. TRUE / FALSE - Electroforming removes metal from a mandrel.

2. TRUE / FALSE - Titanium can undergo superplastic deformation to be fully shaped by mating molds.

3. The part below is to be made from sheet metal. The dimensions specified are for the final part. The aluminum sheet metal has a thickness of 1/16”, and all radii are 1/16”



a) Using allowances for bend radii, determine the actual size of the blank for this piece. Draw a dimensioned sketch.
b) Create a complete process plan for this part, from sheet metal on a roll, to a final part.
c) What is the largest force required to a) bend the part? b) to shear the part? State your assumptions.
d) Give an example (and short reason) of a part best suited for production by,
- Hydroforming
- Spinning
- Magnetic Pulse Forming
- Stamping
- Superplastic Forming
- Powder Metallurgy
- Stereolithography
- Solid Ground Curing

4. If we can reduce sheet thickness by rolling, could this also be done by stretching the sheet? State the relative benefits of each method.

5. Spreading in rolled sheets increases as friction decreases, the material becomes thicker relative to width, and the roller radius becomes smaller. Describe why all three cases are true.

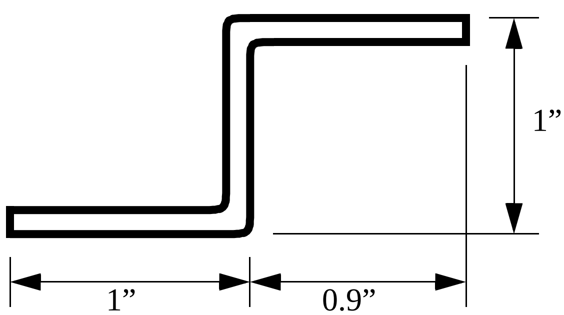
6. We are given a 1020 steel strip that is 1.0m wide, and 6mm thick. It is rolled to a thickness of 4mm. If the rollers are rotating at 300rpm and have a radius of 15cm, what is the roll force?

7. A sheet is being rolled in a set of tandem rollers. The original sheet thickness is 5mm, at the following stages it is rolled to 3.5mm, 2.8mm, 2.4mm and finally to 2.1mm. If the speed of the sheet entering the first rollers is 20m/s, calculate the drafts for each set of rollers, and the velocity of the sheet after each set of rollers.

8. Name 5 components that would be suitable to manufacturing with spinning.

9. a) Derive the equation for the tensile stress in the outermost fibers of a sheet of thickness ‘T’ that has been bent to a radius ‘r’.

10. Sheet metal is bent to have the profile below. The steel sheet thickness is 1/16”, and the bend radii are both 1/8”. (Note: Assume K = 0.5)



a) Do appropriate calculations to determine the length of the sheet metal before bending.
b) If the steel cannot be elongated more than 10%, can this part be made?

11. List and briefly describe 10 different processes for working and forming sheet metals.

12. From your own experiences describe a part that would be good to make with super plastic forming.

13. What is unique about diffusion bonding?

14. Design a die for hydroforming a barbecue propane tank.

15. How can you visually determine if a thread has been rolled or cut on a lathe?

16. We are rolling a 72” wide 9/64” thick aluminum sheet to 7/64” thick. If the roller has a diameter of 10”, and is rotating at 500RPM, What is the roll force and torque?

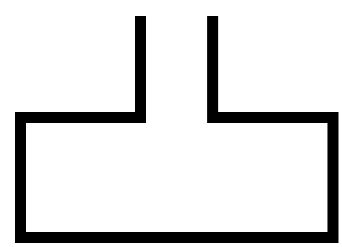
17. Show with figures how the mannesman process creates a hole in the center of a round piece.

18. What is the difference between punching and blanking?

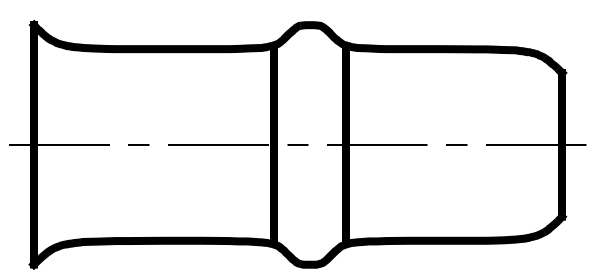
19. What manufactured components could be made by spinning?

20. Step 1. Locate a sheet metal part of reasonable complexity. Show the part to me to verify that it is a good complexity.
Step 2. Develop a process plan for the part. The plan should consider a reasonable operation sequence, as well as suitable machines. This must include estimation of press tonnage, bend allowances, spring-back allowances, punch/shear clearances.
Step 3. Make a mock-up of the part by drawing the part on a computer. Print the drawing, and glue it to a thicker paper or plastic backing. Bend/shear/punch/etc the backing to get the desired shapes.

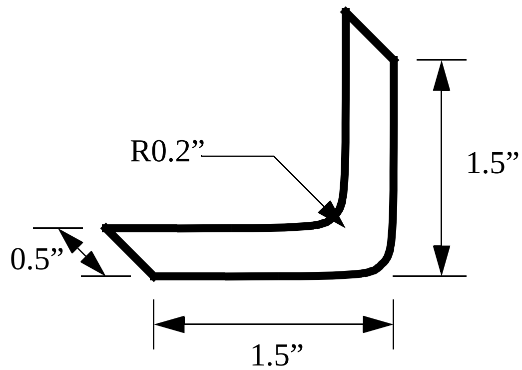
21. How could a long piece with cross section shape shown below be made by rolling?



22. Describe three different methods for making the following round part with sheet metal. Recall that we saw a similar part at MetalFlow.



23. The following piece has been made with 1/16” sheet steel and has the given dimensions.



a) What are the dimensions of the unbent piece? Draw a simple sketch.
b) What will the maximum strain be on the outermost fibers?
c) Is the piece likely to break?
d) What force will be required to shear the four sides of the piece (one at a time) if the UTS of the material is 300MPa?

49. FORGING (to be expanded)

• The forging process typically involves,

1. Having material in a bulk form such as billet, bar, ingot, etc. The material may be heated.
2. Developing dies for the final part.
3. The material is placed between dies, and the dies are closed with force.
4. As the dies close the material reforms.
5. The material may be repositioned, or placed between another die set for continued shaping.
6. The final part is trimmed and prepared for use.

49.1 PROCESSES

49.1.1 Open-Die

49.1.2 Impression/Closed Die

49.1.3 Heading

49.1.4 Rotary Swaging

50. EXTRUSION AND DRAWING

50.1 DIE EXTRUSION

50.1.1 Hot Extrusion

50.1.2 Cold Extrusion

50.2 HYDROSTATIC EXTRUSION

50.3 DRAWING

50.4 EQUIPMENT

50.5 PRACTICE PROBLEMS

51. ELECTROFORMING

• Basic process,

1. A collapsible/removable metal mandrel is placed in an electrolyte solution (this will be the cathode).
2. A conductive bar of pure metal is put in the solution (this will be the anode).
3. Current is applied, and atoms liberated from the bar coat the mandrel.
4. The part is removed when enough metal has built up.
5. Rinse the part and strip it from the mandrel.

• The mandrel should be created to have a negative impression of the part to be made.

• agitating the electrolyte speeds deposition.

• Typical metals used are,

- gold- silver
- lead
- nickel (very good properties)
- copper (very popular)
- iron
- aluminum
- zinc

• Advantages,
  - 0.0005” accuracy is possible
  - very good reproduction of mandrel
  - walls down to 0.001”
  - complex shapes possible
  - no theoretical limits to size
  - laminate parts possible
  - high metal purities possible

• disadvantages,
  - production of 0.001-2” per hour
  - exterior surfaces hard to control
  - thin walled products preferred
  - limited material selection
  - edges, deep recesses and corners not suited to electroforming.

• Permanent mandrels,
  - generally the part is a male or female mate that lifts off easily.
  - a tapered shape makes parts easy to remove

• Disposable mandrels,
  - these mandrels often have undercuts that stop a part from sliding off
  - the mandrel can be dissolved, broken, etc.
  - an example is aluminum mandrels that can be dissolved in sodium hydroxide with no effect on a nickel part.

• Flexible Mandrels,
  - a collapsible reusable mandrel that a part is formed about.
  - If the mandrel is made from a material such as PVC, it must have a conductive coating applied before every use.

• Applications,
  - plastics
  - electronics
  - aerospace
  - printing
  - appliances

• Examples,
  - record pressing plates
  - large reflectors
  - complex piping (thin seamless pipe)

51.1 PRACTICE PROBLEMS

52. COMPOSITE MANUFACTURING

• Each material has desirable properties, but in most situations the perfect material is never found.

• Composites allow mixing of materials to get the best of both.

• BASIC PRINCIPLE: different types of materials are blended together. The materials are often quite different in terms of properties, and the results are a new material that has many of the desired properties of each material.

• Examples
- clay bricks with embedded straw
- reinforced concrete
- samurai swords with steel/iron alternation of layers
- steel belted radials
- graphite tennis racquets
- fishing poles

• for reinforced plastic composites, 2,500,000,000 pounds of plastic based composites were shipped in a wide variety of products in the mid 80's

52.1 FIBER REINFORCED PLASTICS (FRP)

• Typical properties that may be desired are,
- light weight
- stiffness
- strength
- heat resistant
- impact resistance
- electrical conductivity
- wear resistance
- corrosion resistance
- low cost

• Some notable applications are,
- Automotive - engine blocks, push rods, frames, piston rods, etc.
- Electrical - motor brushes, cable electrical contacts, etc
- Medical - prostheses, wheel chairs, orthofies, etc.
- Sports equipment - tennis racquets, ski poles, skis, fishing rods, golf clubs, bicycle frames, motorcycle frames
- Textile industry - shuttles
- etc.

- Some advantages are,
  - composites provide a maximum tensile strength to density ration approximately 4 to 6 times greater than steel or aluminum
  - can provide a maximum material stiffness to density ratio of 3.5 to 5 times that of aluminum or steel
  - high fatigue endurance limits
  - absorb higher impact energies
  - material properties can be strengthened where required
  - corrosion potential is reduced.
  - joints and fasteners are eliminated or simplified

- Some disadvantages are,
  - If either material is susceptible to local solvents, the composite cannot be used
  - materials can be expensive
  - design and fabrication techniques are not well explored and developed.

- fibres are often graphite, glass, aramid, etc.

- the fibres are supported in the matrix, quite often a polymer, epoxy, etc.

- The polymer matrix is often referred to as the resin

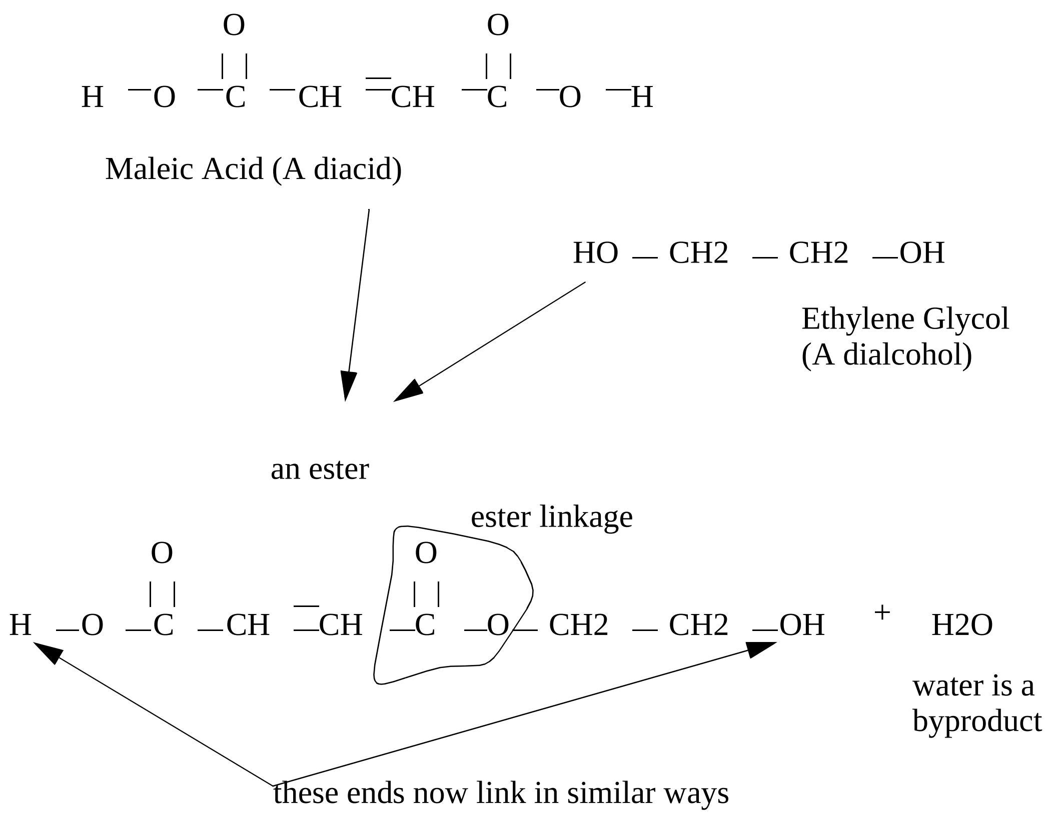
- The matrix transfers the load to the reinforcement fibres, and it protects the fibres from environmental effects.

- Resins tend to be thermosetting, or thermoplastic

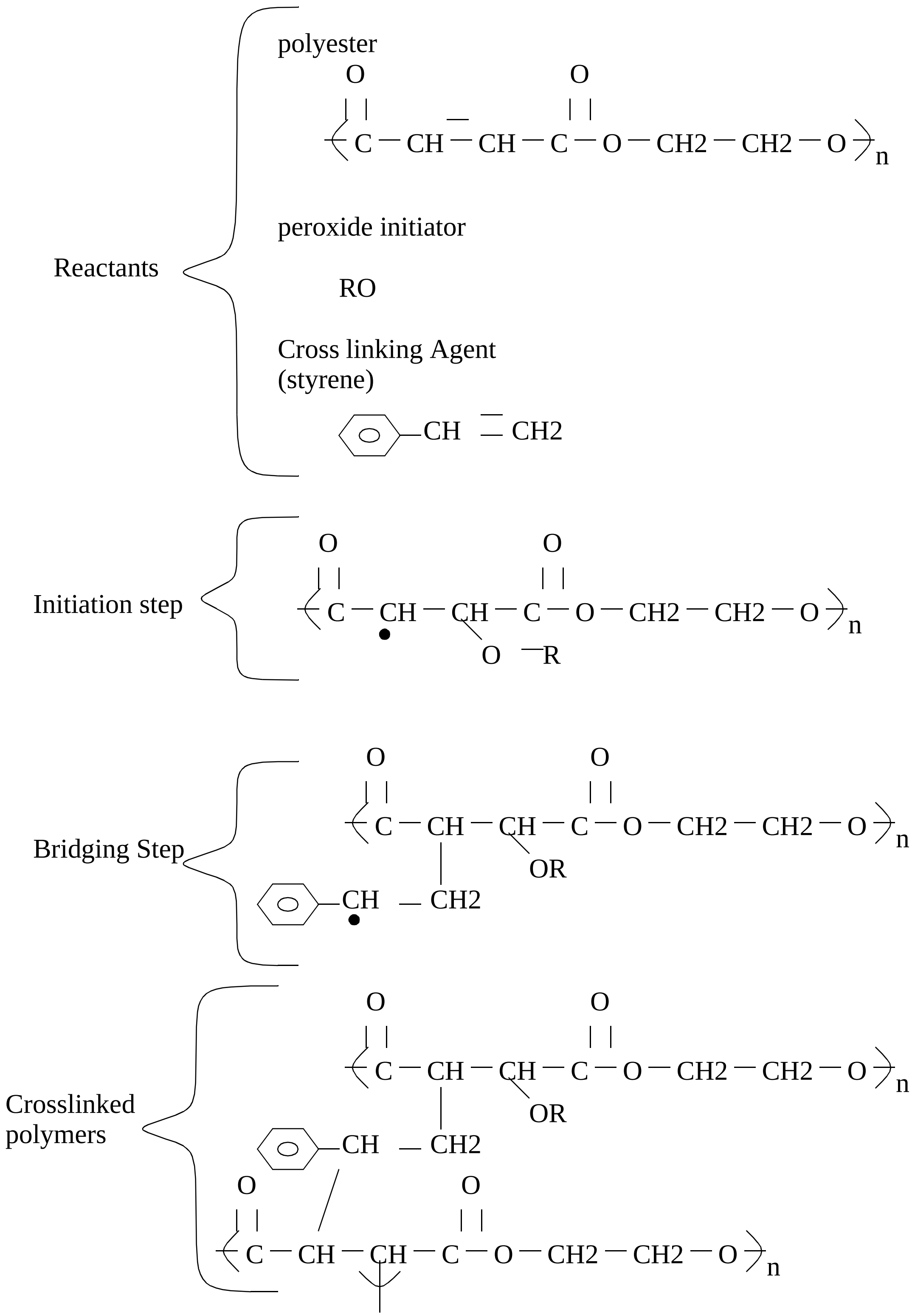
  Thermoplastics - melt, and harden with temperature

  Thermosets - undergo a chemical change, and cannot be “recast”. The setting is often heat activated.

- Polyester resins are quite common. The process often begins with molecules like a dialcohol, and diacid. These then cure into a solid polymer.



• These reactions create very long chains of polymers in a sort of gel, but the next step involves cross-linking them to make things stiff


Reactants
polyester
peroxide initiator
RO
Cross linking Agent
(styrene)
Initiation step
Bridging Step
Crosslinked
polymers

- Various chemical reactions, and physical properties can be altered by changing the chemicals above. Rates of reaction can be accelerated with higher temperatures.

- The initiator is often stored separately from the other reactants to prevent cross linking before use. This may happen spontaneously, and so the chemicals should be discarded if too old.

- Epoxies can also be used, they can be expensive and toxic, but they generally have better overall performance than polyesters.

- Other general categories are,
    - Polymides and Polybenzimidazoles
    - Phenolics and Carbon matrices
    - Thermoplastics
    - Ceramic matrices
    - Metal matrices

- Polyesters are generally inexpensive, and can be modified for other properties.

- Epoxies are used when the matrix must have good adhesion, strength and corrosion resistance in severe environments.

- Polyimides are used for high temperature applications (up to 600 F/316 C) but are difficult to process

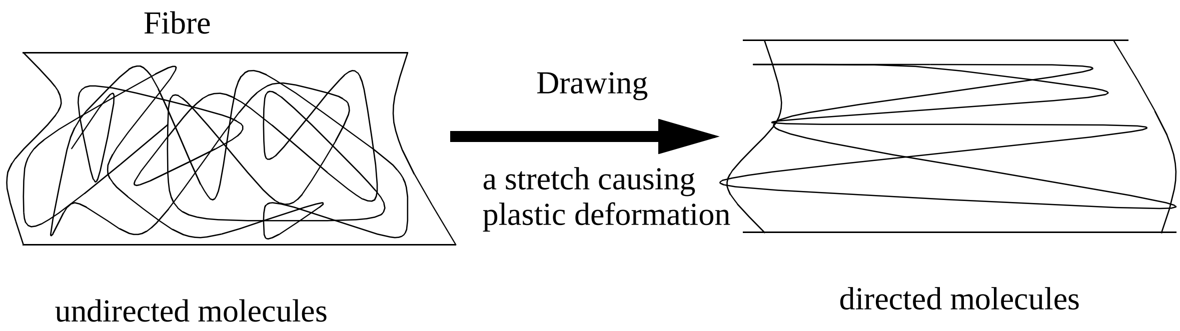
- Phenolics are good for thermal insulation

- Ceramics are used for high temperature, low strength applications.

- Reinforcements in materials can be
    - fibres - long directional filaments
    - particles - small non-directional chunks
    - whiskers - small directional filaments

- Fibres have very long lengths with respect to the surrounding material, and tend to have a significantly higher strength along their length.

- Fibres are often drawn to align the molecules along the fibre length



• Glass fibres are basically made by,

1. Mixing silica sand, limestone, boric acid, and other minor ingredients
2. The mixture is heated until it melts at about 2300F/1260C
3. Letting the molten glass flow through fine holes (in a platinum plate)
4. The glass strands are cooled, gathered and wound. (protective coatings may be added.)
5. The fibres are drawn to increase the directional strength.
6. The fibres are woven into various forms for use in composites

• There are three common glass types used, E, S, C

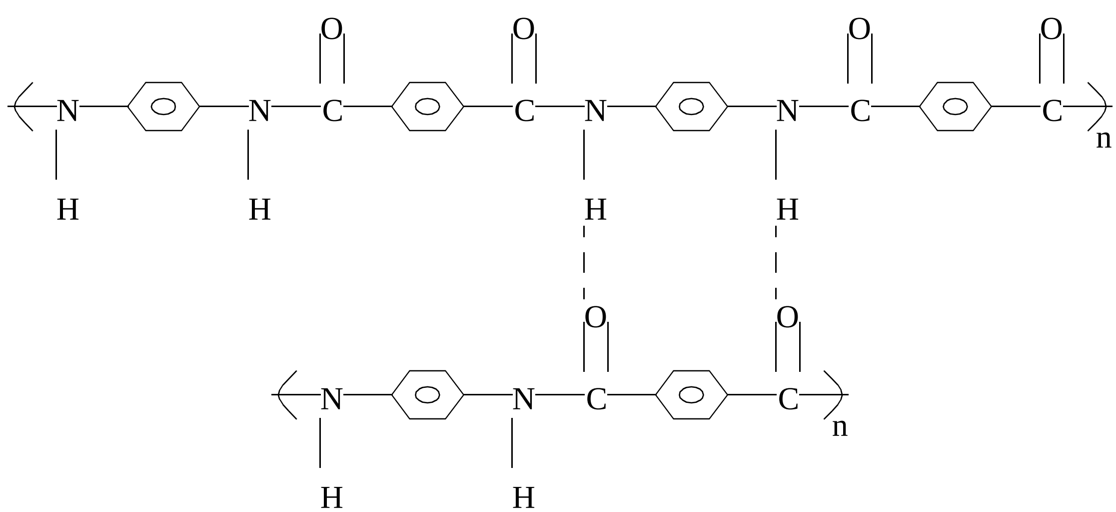
E - less expensive
S - 40% stronger than E, and more resistant to temperature
C - well suited to corrosive environments

Property	Type of glass		
	C	E	S
Density(g/cc)	2.49-2.50	2.54-2.62	2.48-2.50
Tensile Strength (ksi)			
@72F	440-480	500	665
@700F	-	380	545-645
@1000F	-	250	350
Tensile Modulus (Msi)			
@72F	10.0	10.5	12.4
@1000F	-	11.8	12.9
Coef. of thermal expansion (in/in/F)	4.0	2.8	3.1
Coef. of thermal conductivity (BTU-m/hr/sq.ft./F)	-	72	-
Specific Heat, @72F	0.188-0.212	0.193-0.197	0.176
Softening Point, (F)	1380-1382	1545-1555	1778
Dielectric Strength, V/mil	-	262-498	330
Dielectric Constant			
@ 60 H2	-	0.003-0.005	0.003-0.013
@10^6 H2	0.008	0.002-0.0025	0.003-0.0034
Index of refraction	1.532	1.547-1.562	1.523-1.525
Chemical resistance			
(% weight gain after 24 hr expose.)			
In H2O	1.1	0.7	0.7
In 10% HCl	4.1	42	3.8
In 10% H2SO4	2.2	39	4.1
In 1% Na2CO3	24	2.1	2.0

• Carbon Fibres are among the highest strength and modulus materials known.

Fibre	Typical diameter (micro m)	Specific Gravity	Tensile modulus (GPa)	Tensile Strength (GPa)	Strain to failure (%)	Coeff. of thermal exp. (micro m/C) (0 - 100C)	Poisson's ration
Glass							
E glass	10	2.54	72.4	3.45	4.8	5	0.2
S glass	10	2.49	86.9	4.30	5.0	2.9	0.22
PAN-carbon							
T-300c	7	1.76	228	3.2	1.4	-0.1to-0.5	0.2
ASd	7	1.77	220	3.1	1.2	-0.5to-1.2	
T-40c	6	1.81	276	5.65	2		
HMSd	7	1.85	344.5	2.34	0.58		
GY-70e	8.4(bilobal)	1.96	483	1.52	0.38		
Pitch-carbon							
P-55c	10	2.0	380	1.90	0.5	-0.9	
P-100c	10	2.15	690	2.2	0.31	-1.6	
Kevlar 49f	11.9	1.45	131	3.62	2.8	-2	0.35
Boron	140	2.7	393	3.1	0.79	5	0.2
SiC	133	3.08	400	3.44	0.84	1.5	
Al2O3	20	3.95	379.3	1.90	0.4	8.3	

• Aramids (Kevlar) fibres are shown below. These do not need to be drawn as they are already in the correct orientation when produced.



• aramid fibres come in bundles of 134 to 10,000 filaments

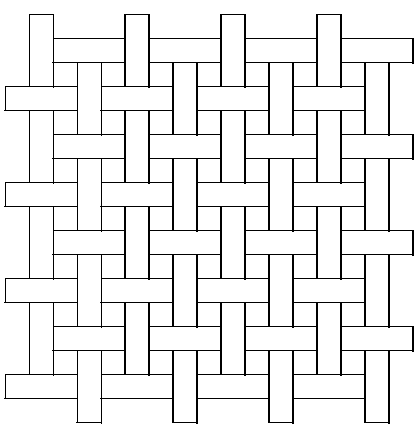
• kevlar properties are,

Kevlar #	29	49	149
Tensile modulus (MPa)	83	131	186
Tensile strength (Mpa)	3.6	3.6	3.4
Elongation (%)	4	2.8	2
Density (g/cc)	1.44	1.44	1.47

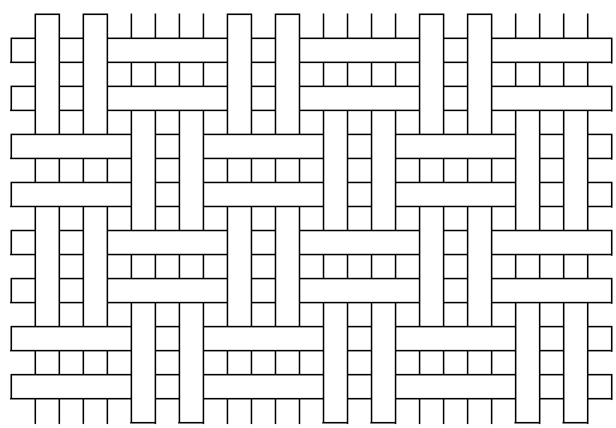
• Other popular fibre types are Boron, Silicon, Carbide, Alumina, etc.

• The fibres come in a variety of configurations,
- Filament - a single fibre
- Strand - Could refer to a single fibre, or an untwisted bundle of filaments
- Tow - A bundle of untwisted fibres, often a predetermined number.
- Yarn - A twisted tow
- Roving - A number of yarns pulled together without twisting
- Tape - a thin and wide run of parallel fibres
- Woven fabric - yarns and tows are interlaced to create flat cloth
- Braids - yarns and tows are woven into tubular shapes
- Mat - chopped fibres create an undirected pattern in a flat cloth. A binder holds the fibres together.

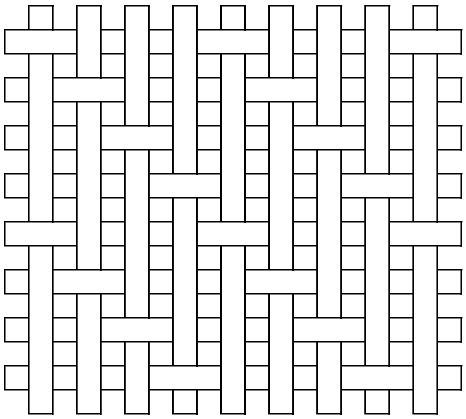
• There are different weave types used, these provide different workabilities, air removal, distortions, etc.



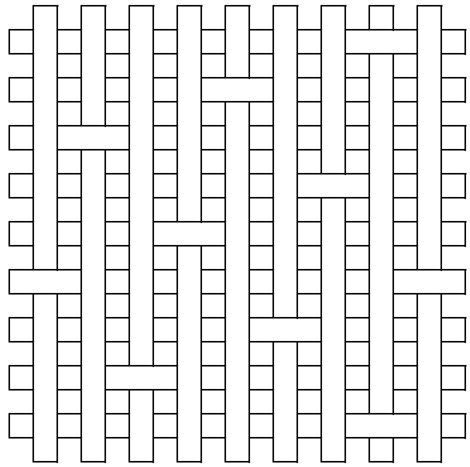
plain weave



basket weave



crowfoot satin



long-shaft

• weaves can be made from single fibre types, or combinations

• The relative material properties for composites are seen in the figures below

RTW - Rigidity to weight
STW - strength to weight
Strain - failure strain
UTS - ultimate tensile strength
Yield - yield strength
USS - Ultimate shear strength
UCS - Ultimate compressive strength

Material	Spec. Grav.	E (GPa	G GPa	UTS (GPa)	Yield (MPa)	RTW	STW	Strain (%)	Poiss	Therm	USS (MPa)	UCS (MPa)
Boron & epoxy (unidirectional, along fiber)	1.99	207	6.4	1585				0.5	.21			2482
Boron & epoxy (unidirectional, across fiber)	1.99	19		62.7				0.5	.21			
boron 6061 & Al (unidirectional, along fiber)	2.35	220		1109	na	9.54	48.1	0.5				
carbon & epoxy (high strength, unidirectional, along fiber)	1.55	137.8	5.7	1550	na	9.06	101.9	1.4	.25		60	1172
carbon & epoxy (high strength, unidirectional, across fiber)	1.55	9.0			na				.25			
carbon & epoxy (high modulus, unidirectional, along fiber)	1.63	215	5.9	1240	na	13.44	77.5	0.4	.2		72	620
carbon & epoxy (high modulus, unidirectional, across fiber)	1.63	13.8		86.2	na				.2			
carbon & epoxy (quasi-isotropic)	1.55	45.5		579	na	2.99	38					
E-glass & epoxy (unidirectional, along fiber)	1.80	39.3	4.8	965	na	2.16	53.2	5	.3		83	620
E-glass & epoxy (unidirectional, across fiber)	1.80	4.8		96.5	na			5	.3			
GY-70 & epoxy (unidirectional, along fiber)	1.69	276	4.1	586				0.3	.25		96.5	517
GY-70 & epoxy (unidirectional, across fiber)	1.69	8.3		41.3				0.3	.25			
kevlar49 & epoxy (unidirectional, along fiber)	1.38	75.8	2.1	1378	na	5.60	101.8	3.1	.34		60	276
kevlar49 & epoxy (unidirectional, across fiber)	1.38	5.5		28.3	na			3.1	.34			
S-glass & epoxy (unidirectional, along fiber)	1.82	43		1241	na			5			83	758
T300 & epoxy (unidirectional, along fiber)	1.55	138	6.5	1448				1	.21		62	1448
T300 & epoxy	1.55	10		44.8				1	.21			

• Composites are sensitive to temperature and humidity during curing.

• When dealing with cyclic loading over a million cycles
  - Aluminum and steel design with 0.1 of the normal yield strength
  - Composites design with 0.5 of normal yield strength

• Composites in general are very easy to shape, and form, this is not always possible with other high strength materials

• Composites are anisotropic and have good strength along the fibre length, but reduced strength across the fibre axis.

• Elongation of composites is typically linear up to fracture at 1% to 2% elongation

52.2 COMPOSITE MANUFACTURING

• The basic process involves,

1. creation of a mold/form
2. Preimpregnation of the fibres (or the later addition of resin)
3. Applying fibres to the mold or form
4. Applying resin if not a prepreg
5. curing of composite in oven (possibly an autoclave)
6. finishing to remove excess, etc.

52.2.1 Manual Layup

• Commonly used for polyester and fiberglass

• Wet Layup
- the dry fabric, or mat is laid in the mold. Resin is then poured on and then rolled or squeegeed evenly over the surface, with attention to removal or air pockets. This is done in layers until the part is done. Fabric can be prewet before laying to allow better fibre/matrix ration control. A parting agent, such as silicone is applied to the mold to allow easy removal or the finished part. Vacuum bags can be used to: remove trapped air/voids trapped in the matrix that weakens the composite; pull the fabric to the mold; compress the composite layers.
- molds are often made from wood, plater, plastic, composites
- the surface of the part that touches the mold will be the good surface (take a very good opposite of the mold). The back surface will be rough.
- Curing is often done at room temperature, but hot air blowers and infrared lamps can accelerate the process.

• Advantages of wet layup
- tooling can be made of any material that can withstand a small pressure.
- tooling can be easily changed.
- expensive equipment is not required, but a vacuum pump is often use for epoxies, and some polyesters.
- curing ovens are not required.
- highly skilled workers are not required.

• Disadvantages of wet layup,
- condensation type cross linking (of the polymer matrix) cannot be used because pressure would be required to remove entrapped condensate.
- the techniques lead to a great deal of variation between each part.
- resin content tends to be high because pressure compaction is not used.
- voids are common in the matrix.

- the strength of the materials tends to be poorer compared to other composite methods. This is in part because the fabrics have a tight weave and are hard to impregnate with resin.
- resin might run when on non-horizontal surfaces, causing pooling of resign. In these cases higher viscosity resins are often used.
- there is more shrinkage in volumes with higher resin contents.
- only one finished surface is possible.

• Prepreg layup
  - the fibres are purchased with resin already mixed. They commonly come in various widths (3 to 72 inches) and have a leathery feel. They are slightly tacky so that they will stick when formed. (The resins can be thermoplastic or thermoset). After layup the part is vacuum bagged and oven cured. The prepreg materials degrade over time, and should be kept in cool environments.

• Advantages of prepreg layup,
  - because the resins are mixed by the manufacturer, the ratio of components is more closely controlled. The manufacturer also ensures better distribution of the resin in the cloth. The manufacturer also performs most of the operations normally hazardous to health.
  - Automated machines can also be used to overcome efficiency problems
  - typically this method gives better physical properties than the wet layup method

• Disadvantages of Prepreg layup,
  - vacuum bagging is required to properly consolidate layers, and remove voids.
  - expensive curing ovens must typically be used.
  - the vacuum bagging procedure leaves room for more scrapped parts.
  - it can be difficult to bag complex parts.

• During layup the fibre orientations are often arranged at multiple angles.
  e.g. 90, 45, -45, -45, 90, 0 degrees

• Typical fibre content in the matrix is 60%

• Typical desired maximum of air/voids in the matrix is 0.5%. There is about a 7% loss of strength for every 1% of voids, up to 4%.

• Disadvantages of manual layup methods,
  - these methods tend to be slow compared to automated methods
  - surface finishes are not the best possible
  - long cure cycles are required

52.2.2 Automated Tape Lamination

• Basically does layup with automated machine.

• An overhead gantry moves a tape application head across the mold, and up inclined faces to apply a prepreg tape, 3” width is typical. Cutting and trimming is done automatically.

• NC programs direct the tape layup, often in geodesic paths.

• This methods saves time, increases part consistency and precision, but requires programming and is unable to handle some complicated parts.

52.2.3 Cutting of Composites

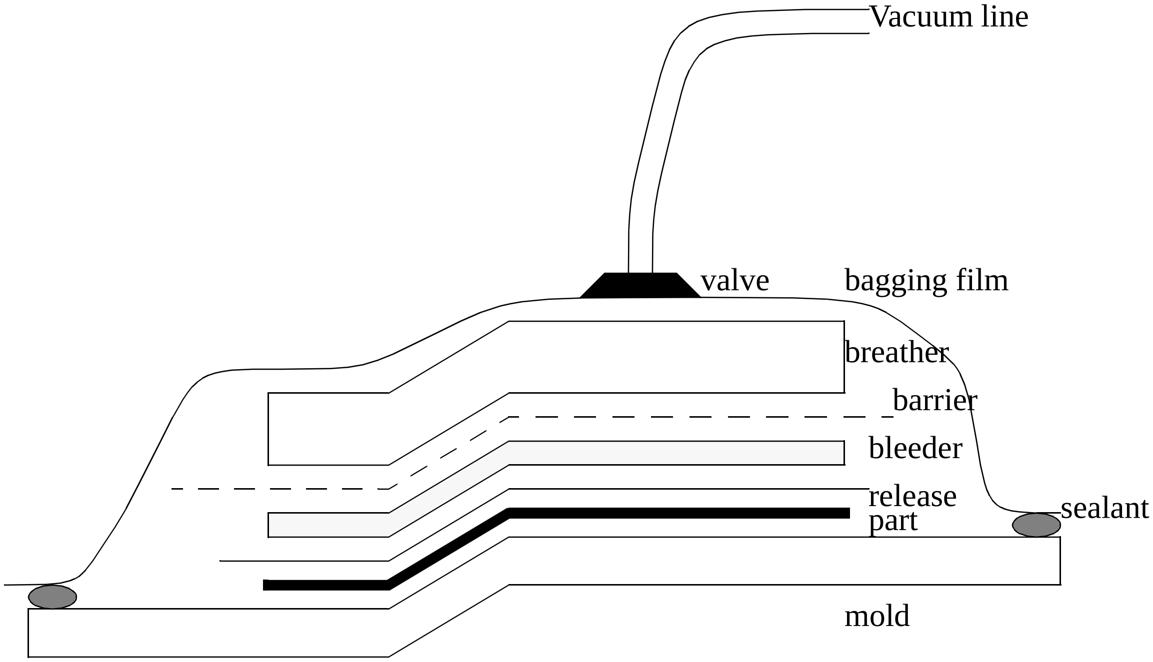
• Cuts can be made with common utility knives, carbide disc cutters (pizza cutters), etc.

• Multiple sheets can be cut at the same time, reducing cost and increasing consistency.

• more advanced cutters use ultrasonics, water jets (care is required not to wet the materials), die cutting, laser cutting, etc.

52.2.4 Vacuum Bags

• Application of a vacuum to the resin helps eliminate residual materials/gas trapped in the uncured resin.
  - air pockets
  - solvents
  - low molecular weight resin components
  - etc.



• Basic steps are,

1. Coat the mold with a mold release agent. This allows the part to easily separate later.
2. Remove prepreg materials from the freezer. Allow the materials to warm to room temperature to reduce condensation - this would contaminate the materials.
3. Build up the layers of the part. Inserts, ribs, etc. may be inserted at this stage.
4. Put a layer of release film on the part. This allows resin to flow out under vacuum, and leaves a good surface for subsequent composite layers to bond to.
5. Add the bleeder layer. This layer will soak up excess resin. It is typically a mat of cotton, polyester felt, or fiberglass (with teflon coat), etc.
6. (Optional) Add a layer of barrier to prevent resin movement to the vacuum valve, but allow air movement. A resin trap should be used in the vacuum system if this step is omitted.
7. (Optional) Add a layer of breather material. This will act as a buffer between the wrinkles in the bag, and the part surface. It also allows better distribution of the vacuum.
8. Apply a sealant around the edges of the part. This can be a tape.
9. Insert thermocouples and any other monitoring devices into the assembly, and ensure that they will not allow air leaks at the sealant. These will be used to monitor cure rates, and control oven temperatures.
10. Put the vacuum bag over the part, and seal at the edges. A typical material is nylon. The vacuum is then applied, and possibly a curing oven is used to accelerate curing.

52.2.5 Autoclaves

• Basically an oven that also uses pressure.

• The part is placed in the pressure vessel, and heated, pressure is applied simultaneously. Vacuum bagging can be used to increase the heating effects.

• The heat accelerates the curing of the thermosets, or melting of the thermoplastic resins.

• The pressure helps bond layers, and remove more voids in the matrix.

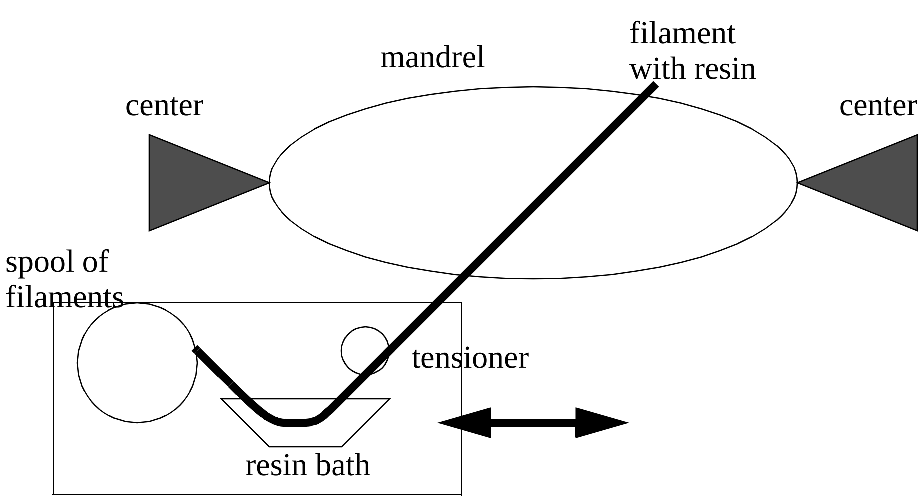
• Inert gases are often injected to prevent fires.

• Although autoclaves are expensive, they produce better parts, and can process many parts at the same time.

52.2.6 Filament Winding

• Basic (Typical) Process - A tape of resin impregnated fibres is wrapped over a rotating mandrel to form a part. These windings can be helical or hooped. This continues until the part is thick enough. There are also processes that use dry fibres with resin application later, or prepregs are used.

• Parts vary in size from 1” to 20’



• mixtures of hoop/helical layers, and layers of different materials allow higher strengths in various direction, and resistance to impact damages.

• geodesic paths are commonly preferred with this approach.

• winding speeds are typically 100 m/min.

• typical winding tensions are about 0.1 to 0.5 kg.

• to remove the mandrel, the ends of the parts are cut off when appropriate, or a collapsible mandrel is used when the parts must remain intact. (one way to do this is with low melt temperature alloys).

• entire parts on mandrels can be cured in autoclaves when desired. A rotating mandrel will help reduce the resin flow effects caused by gravity.

• inflatable mandrels can also be used to produce pretensioned parts that are designed for high pressure applications, or parts that need a liner, and they can be easily removed.

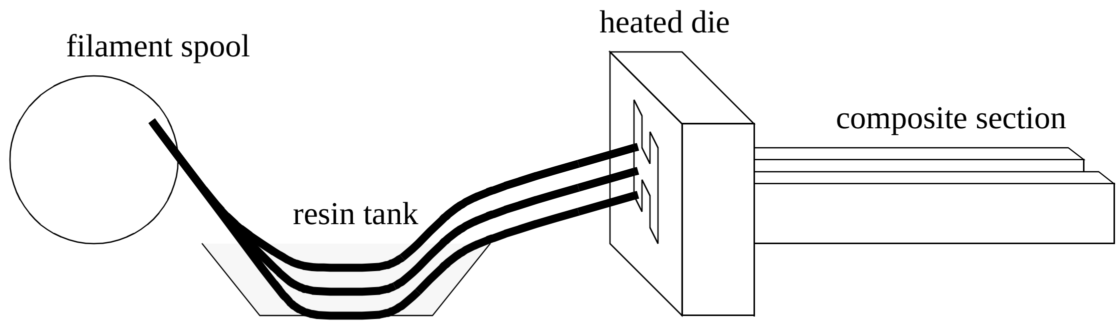
• this method is well suited to round parts, or parts undergoing high hoop stresses.

• advantages
  - can handle a wide variety of part sizes
  - parts can be made with strength in several different directions
  - high percentage of material usage
  - forming after winding will allow non-cylindrical shapes to be made
  - flexible mandrels can be left in as tank liners
  - reinforcement panels, and fittings can be inserted during winding
  - parts with high pressure ratings can be made

• disadvantages,
  - viscosity and pot life of resin must be carefully chosen
  - NC programming can be difficult
  - Some shapes can’t be made with filament winding
  - Factors such as filament tension must be controlled

52.2.7 Pultrusion

• Basic principle - fibers are brought together over rollers, dipped in resin and drawn through a heated die. A continuous cross section composite part emerges on the other side.



• Some points of interest include,
  • Hollow parts can be made using a mandrel that extends out the exit side of the die.
  • Variable cross section parts are possible using dies with sliding parts.
  • Two main types of dies are used, fixed and floating
    - Fixed dies can generate large forces to wet fibre
    - Floating dies require an external power source to create the hydraulic forces in the resin.
  • Multiple dies are used when curing is to be done by the heated dies.
  • Up to 95% utilization of materials (75% for layup).
  • Most fibres are suitable for this process
  • Resins must be fast curing because of process speeds.
  • Rollers are used to ensure proper resin impregnation of the fibre
  • Resins can also be introduced in the die if perforated metal surfaces are used. Prepreg parts are also used.
  • Material forms can also be used at the inlet to the die when materials such as mats, weaves, or stitched material is used.
  • For curing, tunnel ovens can be used. After the part is formed and gelled in the die, it emerges, enters a tunnel oven where curing is completed.
  • Another method is the process runs intermittently with sections emerging from the die, and the pull is stopped, split dies are brought up to the sections to cure it, they then retract, and the pull continues. (Typical lengths for curing are 6” to 24”)

• Typical parameters for,
  - speeds are 0.6 to 1 m/min
  - thickness are 1 to 76 mm
  - diameters are 25mm to 5m

• double clamps, or belts/chains can be used to pull the part through. The best designs allow for continuous operation for production.

• diamond or carbide saws are used to cut sections of the final part. The saw is designed to track the part as it moves.

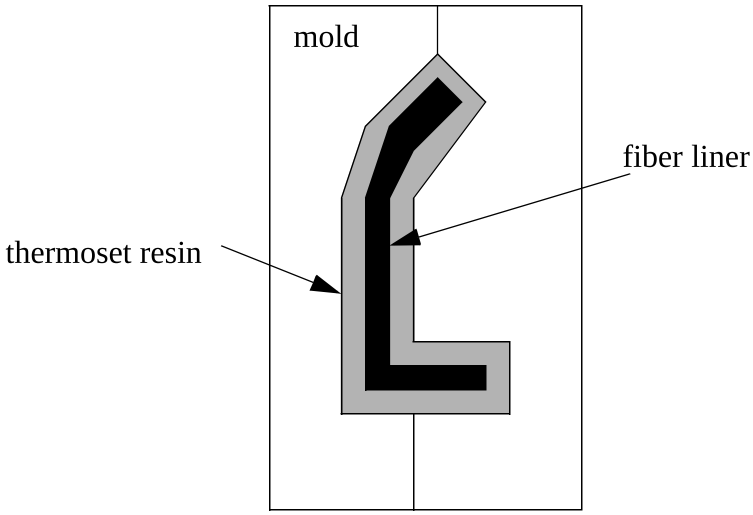
• these parts have good axial properties

• Advantages,
 - good material usage compared to layup
 - high throughput
 - higher resin contents are possible

• Disadvantages,
 - part cross section should be uniform
 - fibre and resin might accumulate at the die opening, leading to increased friction causing jamming, and breakage.
 - when excess resin is used, part strength will decrease
 - void can result if the die does not conform well to the fibres being pulled
 - quick curing systems decrease strength

52.2.8 Resin-Transfer Molding (RTM)

• Basic principle - A mold is filled with fibre, it is closed and resin is injected. The mold is often in vacuum before injection. The pressure of injection wets the fibres.



• This process was used to make car body panels.

• The fibre in the mold can be any that holds its shape during the injection. Layers are often stitched, and bonded.

• Inserts/ribs/etc can easily be put into the mold before it is closed.

• most resins can be used, but low viscosities are useful.

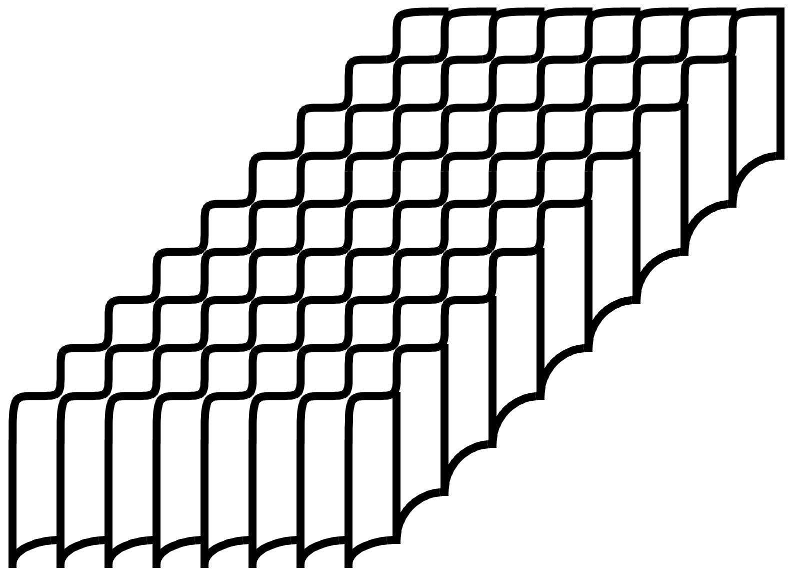
• Advantages,
  - Very large and complex shapes can be made efficiently and inexpensively
  - production times are very short compared to layup
  - low clamping pressures
  - better surface definition than layup
  - inserts and special reinforcements are easily added
  - operators may be unskilled
  - A large number of mold materials may be used
  - part consistency is good
  - worker exposure to toxic chemicals is reduced

• Disadvantages,
  - Mold design is complex
  - material properties are good, but not optimal
  - resin to fibre ratio is hard to control, and will vary in areas such as corners
  - reinforcement may move during injection, causing problems

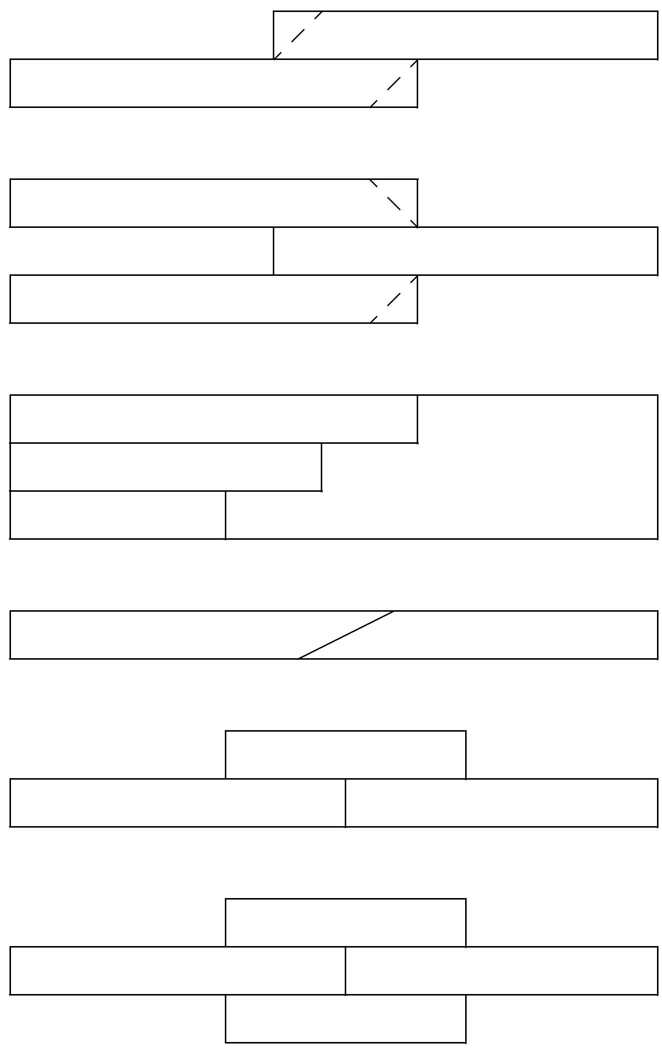
52.2.9 GENERAL INFORMATION

• Resin curing is best done through slow heating, rapid heating will reduce final strength of the part.

• The composite sheets may be strong, but in thin layers they are less capable of resisting bending moments. To overcome this a honeycomb core can be used inside to increase bending resistance. Typical core materials are,
  - PVC foams
  - aluminum honeycombs
  - paper honeycombs



• Joining of composites may be done using adhesives,



Single Lap

Double Lap

Stepped Lap

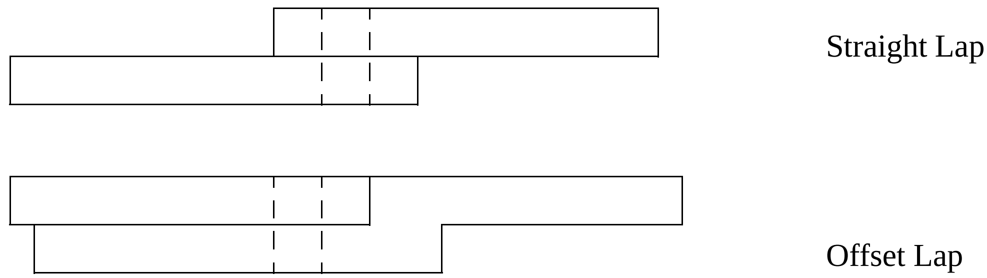
Scarf

Single Overlay

Double Overlay

- There are a wide variety of techniques for joining composites, beyond those shown here. Most attempt to maximize contact areas by using tongues, oblique planes, etc.

- Composites may also be joined with mechanical fasteners, (NOTE: use drilled holes, instead of trying to warp fiber about hole - this leads to resin rich areas)



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Mallick, P. K., and Newman, S., Composite Materials Technology, Hanser Publishers, New York, 1990.

Schwartz, M. M., Fabrication of Composite Materials, American Society for Metals, Metals Park, Ohio, 1985.

Strong, A. B., Fundamentals of Composite Manufacturing, Society of Manufacturing Engineers, Dearborn Michigan, 1989.

52.2.11 PRACTICE PROBLEMS

1.
   a) List at least 5 advantages of composite materials.
   b) List at least 3 disadvantages of composite materials.

2. For thermoset polymers, what effects does cross-linking generally have on the material properties?

3. Which type of glass is good for applications that require,

   a) Low cost?
   b) Operate at high temperatures?

c) Are resistant to corrosion?

4.

a) List 6 different forms (other than single filaments) that composite fibres may be purchased in.

b) What form of composite fibres are best used for pultrusion?

5. If you were making boat hulls with pre-preg composite fibre and large moulds, what steps would be followed?

6. Indicate if the following parts are best made with pultrusion/filament winding/resin transfer moulding.

rocket engine tanks
car body panels
airplane fuselage
a mast for a sail boat

7. A composite section has a honeycomb core 1” thick and can withstand a maximum bending moment of 10KN. How much thicker/thinner would the honeycomb have to be to withstand 1KN?

8. TRUE / FALSE - Multi-directional fibres can be used with stereolithography to increase part strength.

9. What are the major factors that weaken composites? Explain the effect of each.

10. Describe the difference between alloys and composites.

11. Describe the properties of the matrix and fiber materials, and then describe why their combinations is so desirable.

12. What properties does a honeycomb core contribute to a composite part?

13. List 10 products that you have purchased or used that are made of composite materials.

14. What are the advantages and disadvantages of composite materials. What design considerations can be used to overcome the disadvantages?

15. A composite has more than one type of fiber. Why would this be desirable?

16. A part is made of a composite material that is 40% fibers (by area) with a Young’s modulus of 300 GPa, and a matrix of 60 Gpa. The UTS of the fibers is 2000 GPa and 100 MPa for the matrix. If the total cross sectional area of the part is 2cm by 0.2cm, what is the effective stiffness and failure load?

17. Calculate the percentage increase in strength of nylon when e-glass fibers are added.

18. List 5 parts that benefit from the anisotropic properties of composites. Explain why.

19. Corrugated cardboard and composite honeycomb have similar construction. What are the similarities and differences in behavior?

20. List 8 different types of composite manufacturing processes and give an example of a part they are well suited to.

21. Composite materials typically cost more than metals. why are they preferred?

22. List 10 factors determine the strength of a composite materials and parts?

53. POWDERED METALLURGY

• Basic Process - a die cavity is made in the form of a metal part. When the part is to be made, a metal powder is placed in the die, and then compacted. When the die is opened, the part is stiff. It goes through a sintering operation that partially melts the powder and gives the part its strength.

• Powders can be manufactured from most metals inexpensively using techniques such as,
  - atomization/metal spraying - low melting point metals are sprayed to form irregular particles
  - granulations - as metals are cooled they are stirred rapidly
  - electrolytic deposition - often used for iron, copper, silver
  - machining - coarse powders such as magnesium
  - milling - crushers and rollers to break down metals
  - shotting - drops of molten metal are dropped in water
  - reduction - metal oxides are turned to powder when exposed to below melting point gases

• Powders often come in elemental forms and must be blended in correct ratios for metallurgical purposes. Lubricants may also be added to increase powder flow, and to reduce mold adhesion during and after compaction.

• During sintering the metal parts are put in ovens with temperatures just below the melting point. (These ovens also have controlled atmospheres). As the parts are heated the compacted particles melt slightly and bond. There is a reduction in part size.

• Features:
  - For high tolerance parts, a sintering part is put back into a die and repressed. In general this makes the part more accurate with a better surface finish.
  - A part has many voids that can be impregnated. One method is to use an oil bath. Another method uses vacuum first, then impregnation.
  - A part surface can be infiltrated with a low melting point metal to increase density, strength, hardness, ductility and impact resistance.
  - Plating, heat treating and machining operations can also be used.

• Production of magnets:
  - 50:50 Fe-Al alloy is used for magnetic parts
  - Al-Ni-Fe is used for permanent magnets
  - Sintering is done in a wire coil to align the magnetic poles of the material
  - H_2 is used to rapidly cool the part (to maintain magnetic alignment)
  - Total shrinkage is approximately 3-7% (for accurate parts an extra sintering step may be added before magnetic alignment)
  - The sintering temperature is 600°C in H_2

• Conducting contacts can also be made,

Contact material	current level	thermal level	wear resistance	sparking tolerance	density	voltage levels	friction	Contact material
W-Ag, Mo-Ag, W-Cu, Ag-Ni, Ag-CdO								heavy duty contacts, circuit breakers, welding
Mo-Ag	h		x			m		
60-40 Mo-Ag	h		x			m		used as tips on bronze or copper
W-Ag	m		x			a		
W-Cu				x		h		
60-40 W-Cu								used in oil circuit breakers
copper-graphite	h	h	x	x			l	commutators
bronze-graphite	h	h	x	x			l	commutators
silver-graphite	h	h	x	x			l	commutators
tungsten		h	x	x			h	electrodes
molybdenum		h	x	x			h	electrodes
WC-hard metals		h	x	x			h	electrodes

Legend:
- h- high
- l - low
- m - Medium
- x - significant effect
- a - all

• Other applications include,
  - friction parts
  - electrical contacts

• Advantages,
  - good tolerances and surface finish
  - highly complex shapes made quickly
  - can produce porous parts and hard to manufacture materials (e.g. cemented oxides)
  - pores in the metal can be filled with other materials/metals
  - surfaces can have high wear resistance
  - porosity can be controlled
  - low waste
  - automation is easy
  - physical properties can be controlled
  - variation from part to part is low
  - hard to machine metals can be used easily
  - no molten metals

- no need for many/any finishing operations
- permits high volume production of complex shapes
- allows non-traditional alloy combinations
- good control of final density

• Disadvantages,

- metal powders deteriorate quickly when stored improperly
- fixed and setup costs are high
- part size is limited by the press, and compression of the powder used.
- sharp corners and varying thickness can be hard to produce
- non-moldable features are impossible to produce

53.1 PRACTICE PROBLEMS

1. TRUE / FALSE - Heating is involved in powdered metallurgy.

2. TRUE / FALSE - Refractory materials are used as conductors.

3. Describe the sintering process.

4. What advantages does powdered metal have over other processes?

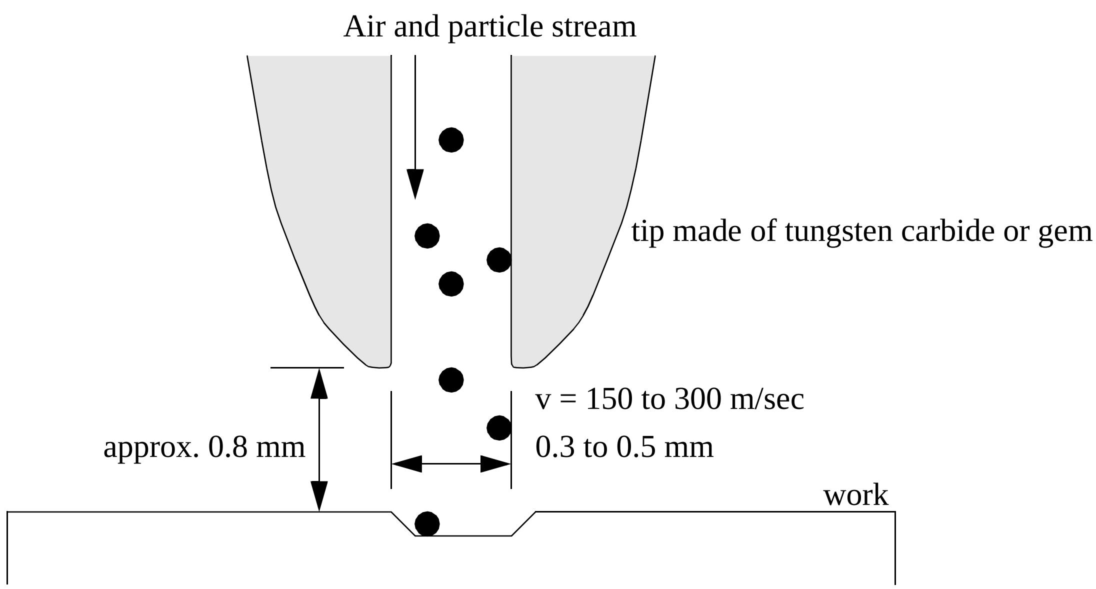
5. What limitations exist in the powdered metal process.

6. How can the porosity in a powder metal part be reduced? How can it be used to introduce advantageous materials?

54. ABRASIVE JET MACHINING (AJM)

• The physics,

1. Fine particles (0.025mm) are accelerated in a gas stream (commonly air at a few times atmospheric pressure).
2. The particles are directed towards the focus of machining (less than 1mm from the tip).
3. As the particles impact the surface, they fracture off other particles.



• As the particle impacts the surface, it causes a small fracture, and the gas stream carries both the abrasive particles and the fractured (wear) particles away.

• Brittle and fragile work pieces work better.

• Material Removal Rate (mrr) is,

$$Q = \chi Z d^3 v^{\frac{3}{2}} \left(\frac{\rho}{12 H_w} \right)^{\frac{3}{4}}$$

Z = # of abrasive particles impacting per unit time

d = mean diameter of abrasive grains

v = velocity of abrasive grains

ρ = density of abrasive grains

H_w = the hardness of the workpiece - the flow stress

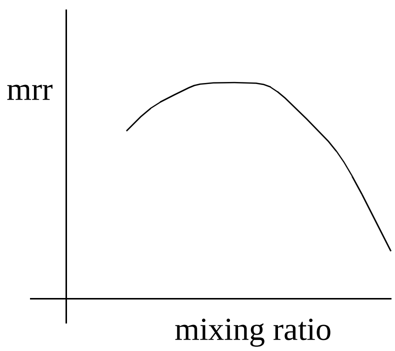
χ = a constant

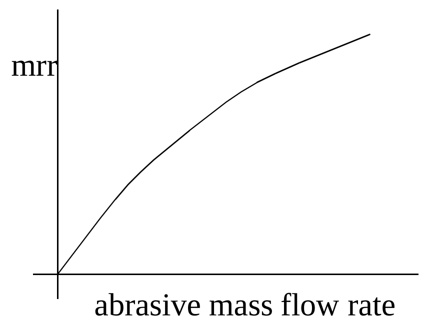
• Factors that effect the process are,
  - mrr
  - geometry of cut
  - roughness of surface produced
  - the rate of nozzle wear

• The factors are in turn effected by,
  - the abrasive: composition; strength; size; mass flow rate
  - the gas composition, pressure and velocity
  - the nozzle: geometry; material; distance to work; inclination to work

• The abrasive,
  - materials: aluminum oxide (preferred); silicon carbide
  - the grains should have sharp edges
  - material diameters of 10-50 micro m 15-20 is optimal
  - should not be reused as the sharp edges are worn down and smaller particles can clog nozzle.

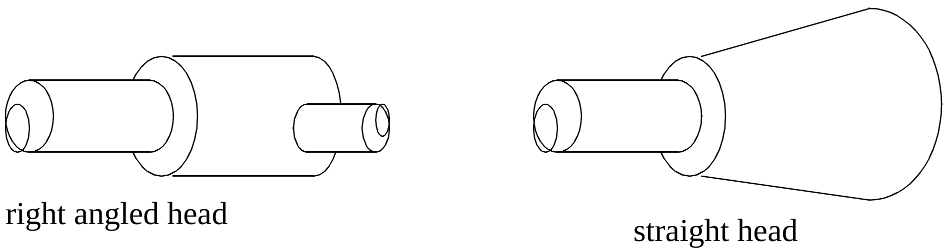
• Gas jet,
  - mass flow rate of abrasive is proportional to gas pressure and gas flow



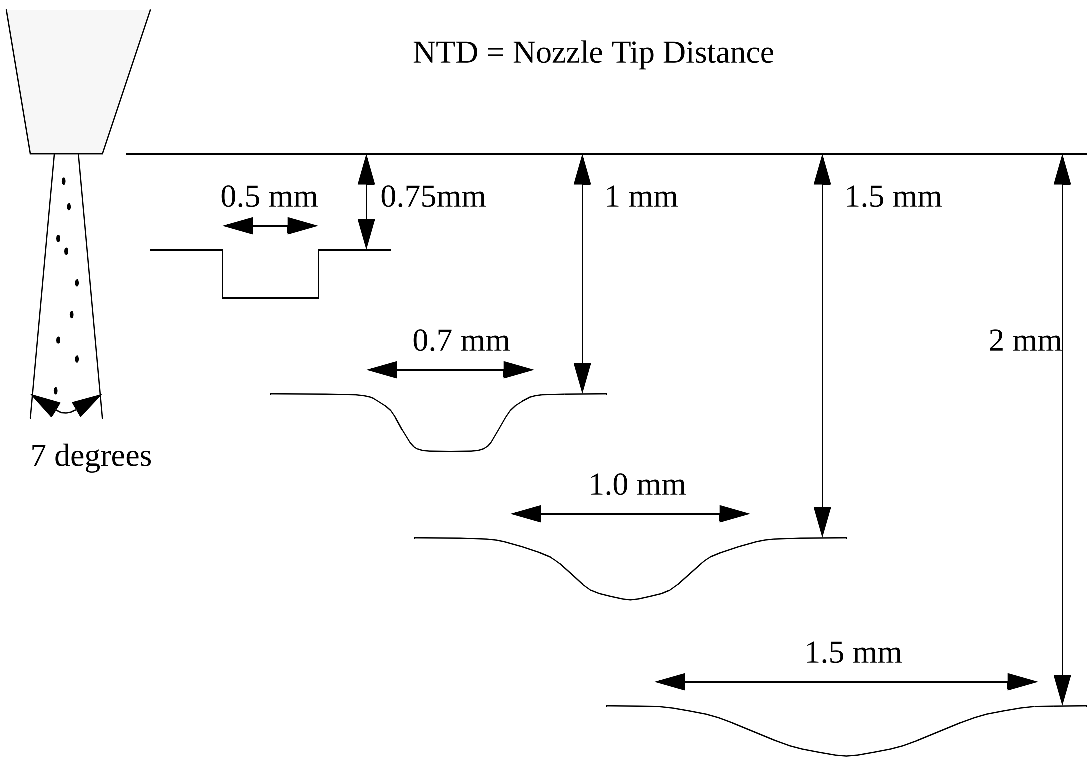


  - pressure is typically 0.2 N/mm^2 to $1N/mm^2$
  - gas composition effects pressure flow relationship

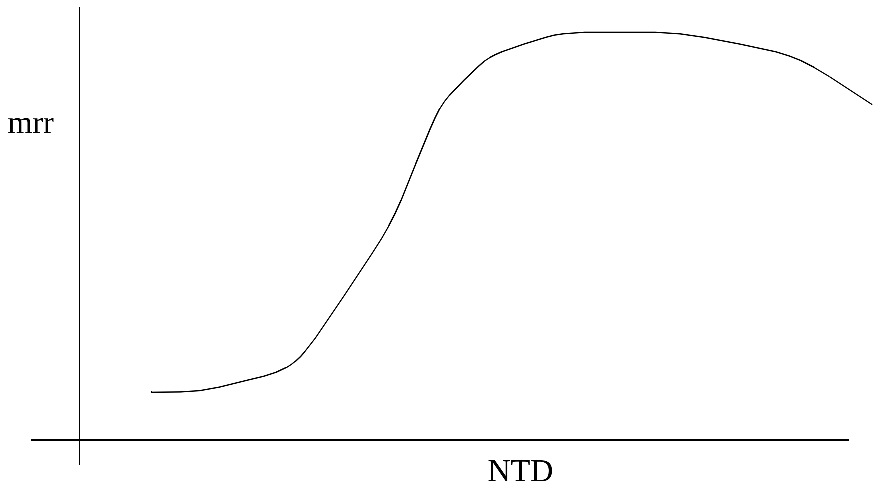
• Nozzle
  - must be hard material to reduce wear by abrasives: WC (lasts 12 to 30 hr); sapphire (lasts 300 hr)
  - cross sectional area of orifice is 0.05-0.2 mm^2
  - orifice can be round or rectangular
  - head can be straight, or at a right angle



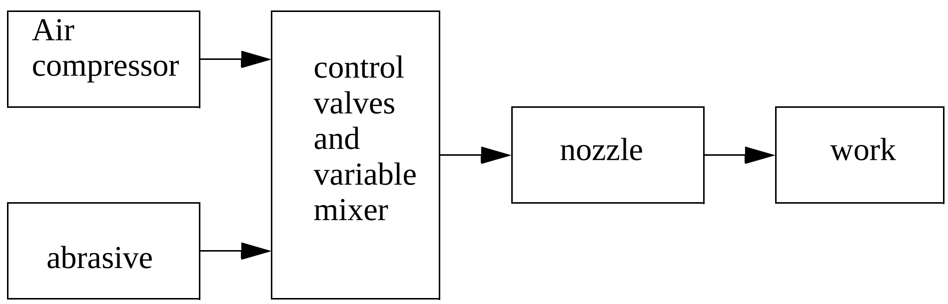
• The relationship between head, and nozzle tip distance.



• Air drag also slows abrasive stream.



• Machines



• Summary of AJM characteristics
- Mechanics of material removal - brittle fracture by impinging abrasive grains at high speed
- media - Air, CO_2
- abrasives: Al_2O_3, SiC, 0.025mm diameter, 2-20g/min, non-recirculating
- velocity = 150-300 m/sec
- pressure = 2 to 10 atm.
- nozzle - WC, sapphire, orifice area 0.05-0.2 mm^2, life 12-300 hr., nozzle tip distance 0.25-75 mm
- critical parameters - abrasive flow rate and velocity, nozzle tip distance from work surface, abrasive grain size and jet inclination
- materials application - hard and brittle metals, alloys, and nonmetallic materials (e.g., germanium, silicon, glass, ceramics, and mica) Specially suitable for thin sections
- shape (job) application - drilling, cutting, deburring, etching, cleaning
- limitations - low metal removal rate (40 mg/min, 15 mm^3/min), embedding of abrasive in workpiece, tapering of drilled holes, possibility of stray abrasive action.

54.1 REFERENCES

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54.2 PRACTICE PROBLEMS

18. TRUE / FALSE - Water jet cutting can chip brittle work pieces.

55. HIGH PRESSURE JET CUTTING

• Typical jet size <0.8mm faster than speed of sound.

• Typical fluid is water.

• Good for slotting.

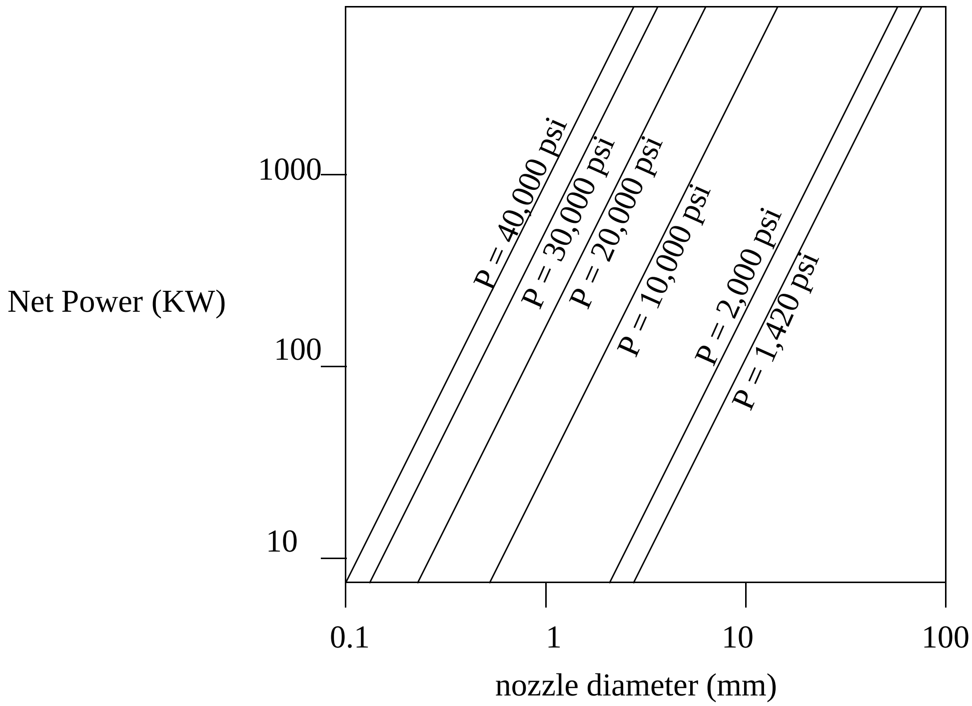
• Used on,
    - metals
    - paper
    - cloth
    - wood
    - leather
    - rubber
    - plastics
    - frozen food
    - ceramics

• Main divisions or use,
    - jet cutting
    - destruction of brittle materials
    - separation of materials

• Typical pressures are 150-1000 MPa and use 8-80 KW.

• Velocities are 540-1400 m/s.

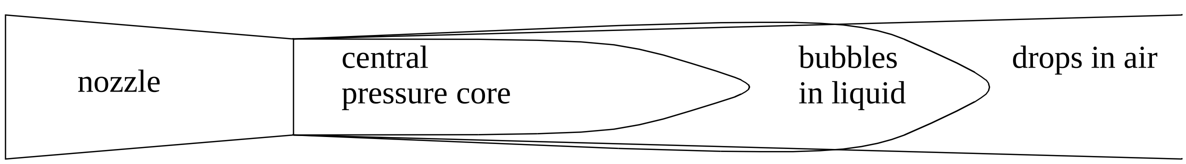
• Typical fluid volume is 0.5 to 2.5 l/min.



• Fluid Pressure Intensifier - hydraulics actuates smaller cylinders, that drive larger cylinders. The larger cylinders intensify air pressure.

• Nozzle - internal diameter reduces 40 to 160 times to the exit tip.

• The exit jet looks like,



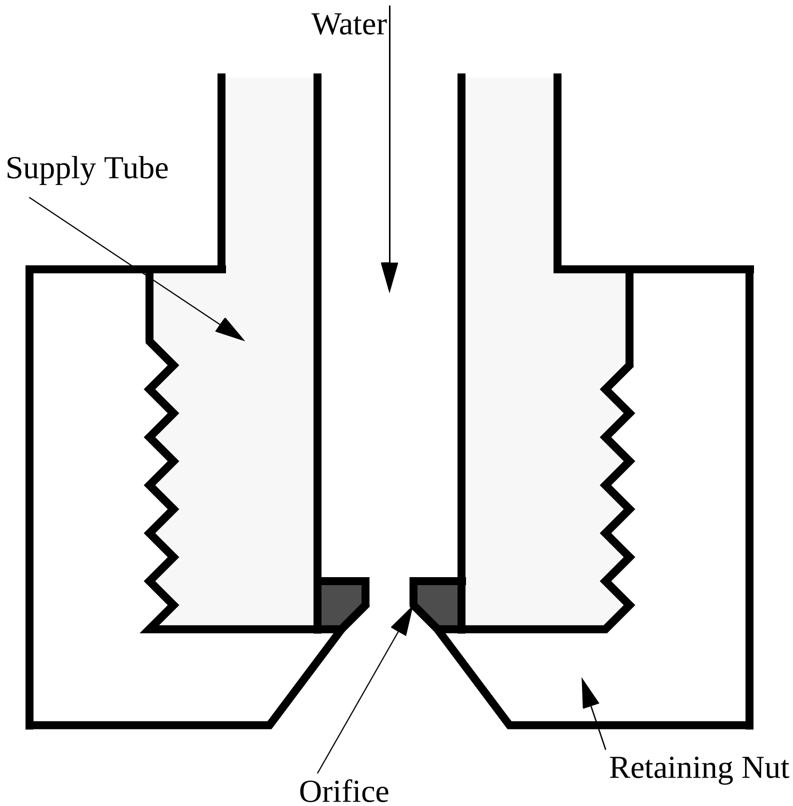
• Cutting - If the material is brittle it will fracture, if ductile or erosive, it will cut well.

• Pulsed cuts can cut deeper, but feed rates must be reduced for acceptable cuts.

• The fluid used must have a low viscosity to minimize energy loses,
  - be non-corrosive
  - non-toxic
  - common and inexpensive

• Water most common, but additives such as alcohols, oils, products and glycerol are used, when they can be dissolved in water (ventilation may be required).

• The typical head is shown below. The orifice is often made of sapphire and ranges from 0.05” to 0.020”



56. ABRASIVE WATERJET CUTTING (AWJ)

- Basic principle a narrow, focused, water jet is mixed with abrasive particles. This jet is sprayed with very high pressures resulting in high velocities that cut through all materials. The water jet reduces cutting forces, and virtually eliminates heating. The basic cutting mechanism is erosions.

- Non-contact and no tool wear.

- Good for materials that cannot stand high temperatures of other methods for stress distortion or metallurgical reasons.

- Developed in 1960s.

- Typical pressures are 10-100 Kpsi - lower pressures are good for soft materials metals need higher pressures. The required jet pressure decreases with the use of harder abrasives.

- Steel plates over 3” thick can be cut.

• The energy in the beam can be expressed with Bournoulli’s equation,

$$(Z_1 - Z_2) + \frac{P_1 - P_2}{\Psi} + \frac{V_1^2 - V_2^2}{2g} = 0$$

$(Z_1 - Z_2)$ is negligable

$$\therefore \Delta P \propto \Delta V^2$$

• The basic system uses,
  - Filters - purifies the water to extend system life
  - Compressors/Intensifiers - increases water pressure
  - Water delivery - tubes and fittings to deliver intensified water
  - Abrasive hopper - to deliver abrasive
  - Orifice/Mixing Chamber/Refocusing Nozzle - to mix the high pressure water, and abrasives
  - Cutting nozzle - to direct the jet
  - NC Gantry - to position the cutting head
  - Catcher - to stop the spent jet

• The velocity of the stream is up to 285 fps (or 1950 mph) about 2.5 times the speed of sound. The cutting energy is proportional to the root of the velocity.

• The pressures may also have transient spikes up to 3 times the base cutting pressure.

• Typical materials,

material	ultimate compression (Kpsi)
titanium	50-135
aluminum	19-110
granite	19
marble	12
wood	5-9
brick	4

• Typical cut width (Kerf loss) is 0.030” and above.

• Typical orifice sizes are 0.007,9,13,15 in.

• The effective jet range is up to 8” for hard materials. Pressure falls off after 1”.

• The jet will have a well behaved central jet surrounded by a fine mist.

• Typical process jet variables are,
  - pressure
  - diameter
  - standoff
  - abrasive feed rate
  - material feed rate

• The greater the amount of energy delivered the,
  - thicker the cut
  - smoother the finish
  - harder the material

• Multiple pass cutting involves making a cut that does not fully penetrate, and does not chip edges, and making subsequent passes. This saves energy but will result in degraded surface quality.

• Advantages,
  - surface finishes can be as good as conventional machining
  - no temperature changes
  - very little scrape produced
  - negligible cutting forces, therefore little or no fixturing
  - fragile/brittle materials can be cut

• The water filter,
  - uses filters to remove microscopic particles that might damage the orifice and other high pressure parts.
  - a traditional pump is used to drive the water through 10 micron, 1 micron and 0.5 micron filters.
  - typical flow out is 1 gallon per minute at normal tap pressure.

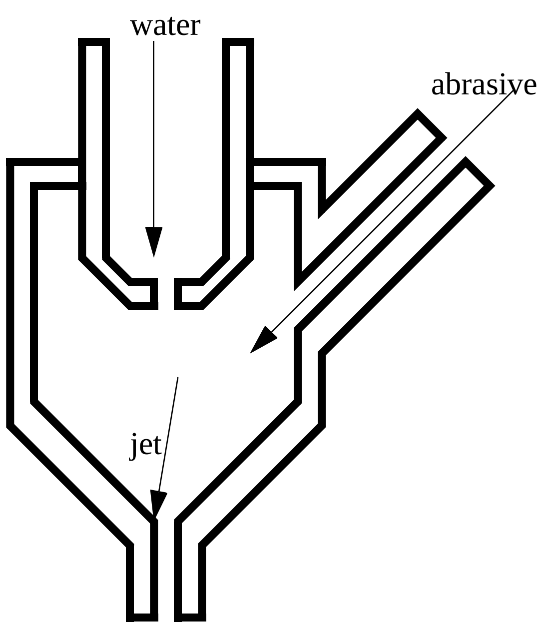
• Intensifiers,
  - basically a small piston driven by a larger hydraulic piston. The opposing cylinders change a large differential volume for a large differential pressure.
  - as the hydraulic unit in the center pumps in both directions, a high pressure is generated in the water cylinders at either end. Check valves allow water flow in and out as appropriate.
  - the pressures generated by the intensifier can be adjusted by modifying the hydraulic pressures.
  - roughly 2Hz.

• Accumulator - acts as a pressurized reservoir for the water.

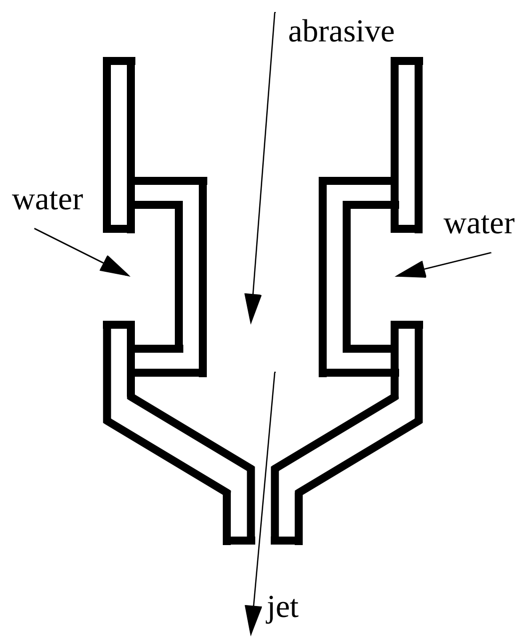
• Tubing and Fittings,

- between the accumulator, and the movable head, a variable dimension delivery system is required.
- at lower pressures flexible rubber hoses would be used, but at these pressures, a coiled stainless steel tube is often used. The ends of the tubes are connected with high pressure swivels.
- a protective sheath is placed about the tubes to prevent damage in the instance of leaks. Flow valves are also used to reduce the chances of damage.

• Mixing head,
- mixes water and abrasive, and focuses for cutting
- combines orifice, mixing chamber, refocusing and nozzle



Single Jet, side feed



Multiple jet, central feed

- Single jet - side feed heads are suited to tight/small applications because of simple head geometry. Some problems with mixing head.
- multiple jet, center feed. Good mixing characteristics, but hard to manufacturing.
- mixing tubes are often made of tungsten carbide or similar materials

• Abrasives,

• The catcher,
- stops the jet after it has passed the cutting surface.
- reduces press, noise, dust, increases safety.
- a water filed tube can be used.
- the jet should be dispersed within the length of the tube (up to 24") shorter tubes need hard materials at the far end.

- some mechanisms use a tank with a 2” steel plate for the bottom.

• General parameters,
    - a larger orifice results in a rougher surface finish
    - surface finish > 100 micro in. (Ra) up to ????
    - deeper cuts give rougher surface finish
    - cutting speeds < 1 ipm up to 5 ipm
    - higher cutting speeds give better finishes
    - surface quality degrades at bottom side first
    - the surfaces tend to have waves, probably caused by intensifier
    - the jet flares from 0.1” to 1”
    - faster cutting speeds result in more flaring

• Generally,
    - slower feeds than laser
    - faster than wire EDM
    - slower than plasma cutters

• Cost is typically $20 to $40 per hour for operation mainly as a function of abrasives.

• Advantages,
    - can cut traditionally hard to cut materials, eg. composites, ceramics, glass
    - no special tooling required

• Disadvantages,
    - hourly rates are relatively high
    - flaring can become large
    - not suitable for mass production because of high maintenance requirements

• Typical machining conditions,

material	thickness (in.)	speed (ipm)
aluminum	0.5/1	5/2.5
stainless steel	0.5/1	2.5/1.5
mild steel	0.5/1	3/2
granite	0.5/1	4/2.5
glass	0.1/2	30/2
PVC	0.1/2	25/1

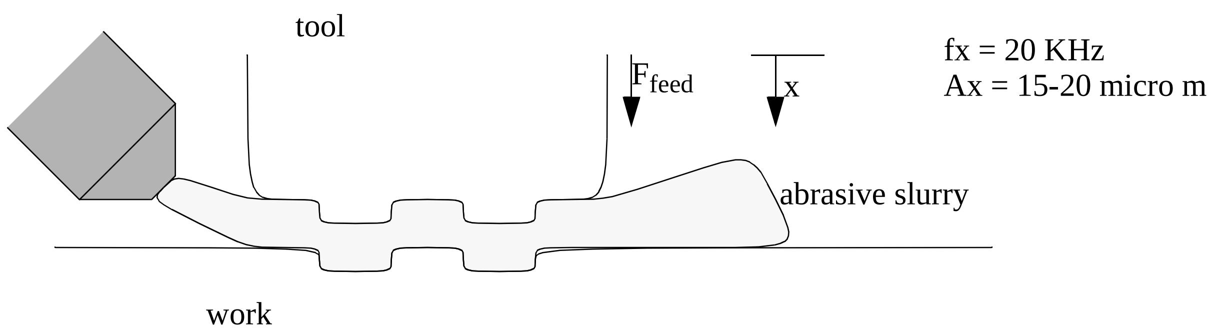
57. ULTRA SONIC MACHINING (USM)

• First built 1950s.

• Originally used for finishing EDM surfaces.

• Best suited to poorly conducting materials, and brittle materials.

• The basic process is a ductile and tough tool is pushed against the work with a constant force. A constant stream of abrasive slurry passes between the tool and the work to provide abrasives and carry away fractured particles. The majority of the cutting action comes from an ultrasonic (cyclic) force applied in addition to the other force.



• The basic components to the cutting action are believed to be,
1. The direct hammering of the abrasive into the work by the tool (major factor)
2. The impact of the abrasive on the work
3. Cavitation induced erosion
4. Chemical erosion caused by slurry

• M.C. Shaw generated a model to estimate the cutting action.

$$Q \propto vZf$$

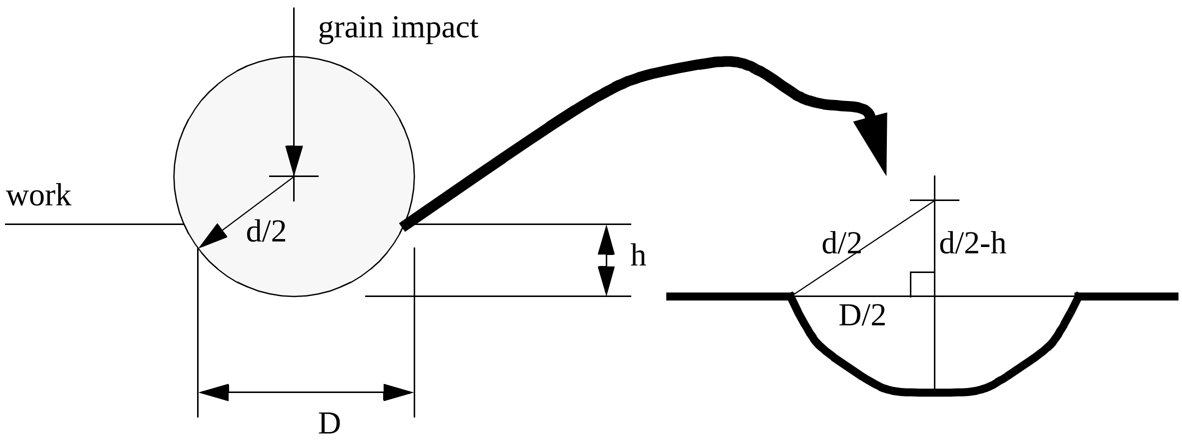
Q = volume of work material removal rate

v = volume of material removed per particle imapct

Z = number of particles im[illegible]

f = frequency (cycles per second)

• Consider the impact pictured below.



$$\left(\frac{D}{2}\right)^2 = \left(\frac{d}{2}\right)^2 - \left(\frac{d}{2} - h\right)^2$$

$$\therefore D^2 = 4dh - 4h^2$$

assume the impact depth ‘h’ is small compared to d.

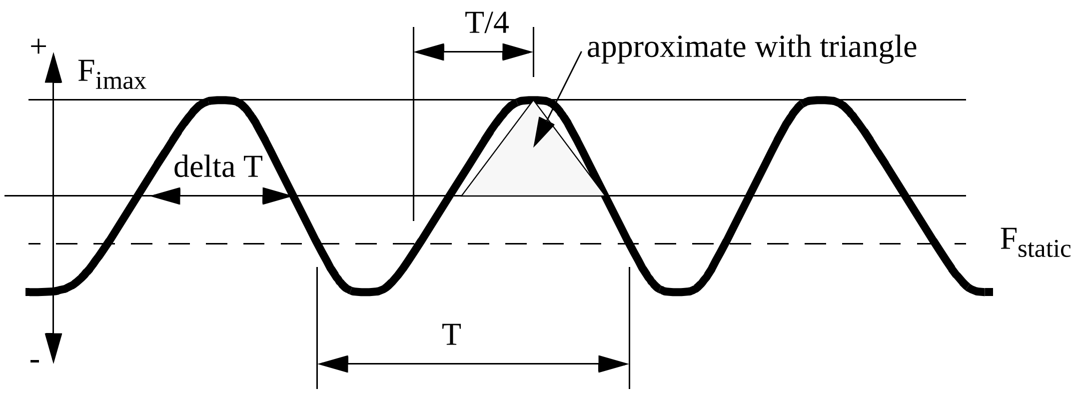
$D \approx 2\sqrt{dh}$

now assume

D^3(volume) $\propto$ v(volume per impact)

$$\therefore Q \propto vZf \propto D^3 Zf \propto (dh)^{\frac{3}{2}} \propto (dh)^{\frac{3}{2}} Zf$$

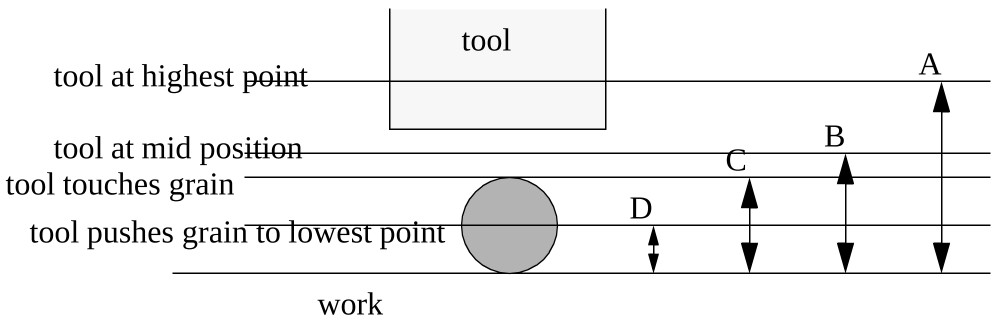
Also assume the force is as shown below,



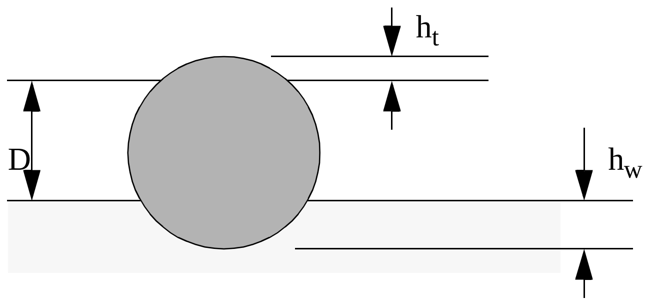
-ve force means no contact, and no force to abrasive

$$F = \frac{1}{T}\int_0^T Fi(t)dt$$

or $F \approx \frac{1}{2}F_{i_{max}}\Delta t\frac{1}{T}$



When the tool has pushed the grain to the lowest point, the tool-grain-work interface looks like,



The total indent is therefore

$h = h_t + h_w$

If A is the amplitude of oscillation of the tool, the average velocity from B to D is,

$$v_{B \to D} \approx \frac{A}{\left(\frac{T}{4}\right)}$$

$$\Delta t \approx \frac{dist}{vel} = h\left(\frac{1}{A}\right)\left(\frac{T}{4}\right) = \left(\frac{h_t + h_w}{A}\right)\frac{T}{4}$$

$$F \approx \frac{F_{i_{max}}}{2}\frac{\Delta t}{T} \approx \frac{F_{i_{max}}}{2}\left(\frac{h_t + h_w}{A}\right)\frac{T}{4}\frac{1}{T}$$

$$\therefore F_{i_{max}} \approx \frac{8FA}{h_t + h_w}$$

This force is applied to 2 grains to give a force per grain

$$F_g = \frac{F_{i_{max}}}{Z}$$

The contact area per grain is

$$A_g = \pi\left(\frac{D}{2}\right)^2 = \pi d h_w$$

Therefore the maximum stress is

$$\sigma_w = \frac{F_{i_{max}}}{\pi Z d h_w} = \frac{F_g}{A_g} = \frac{8FA}{\pi Z d h_w (h_w + h_t)}$$

Assume that the depth of penetration is inversely proportional to the flow stresses (this is reasonable if the other forces and geometries remain constant)

$$\therefore h \propto \frac{1}{\sigma}$$

$$\therefore \frac{h_t}{h_w} = \frac{\sigma_w}{\sigma_t} = \lambda$$

tool/work indentation ratio

Flow stress sigma and Brinell hardness H are the same so,

$$h_w^2 = \frac{8FA}{\pi Z d H_w (1 + \lambda)}$$

We can assume the number of grains per impact is,

$$Z = \chi\left(\frac{C}{d^2}\right)$$

C = concentration of grains in

χ = constant of proportionality

$$\text{thus } h_w = \sqrt{\frac{8FAd}{\pi \chi H_w C(1 + \lambda)}}$$

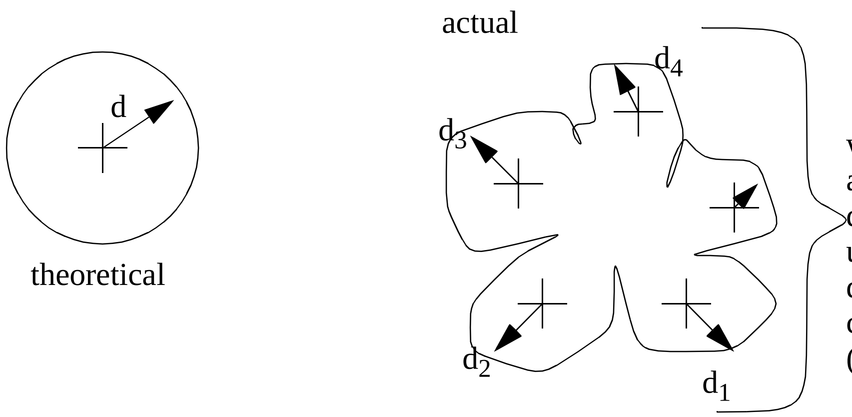
further

$$Q \propto \left[\frac{d8FAd}{\pi H_w C(1 + \lambda)}\right]^{\frac{3}{2}} \chi \frac{C}{d^2} f$$

$$\therefore Q \propto \frac{A^{\frac{3}{4}} d^{\frac{1}{4}} F^{\frac{3}{4}} C^{\frac{1}{4}}}{H_w^{\frac{3}{4}}} f$$

- Material is also removed by grains moving quickly and building up kinetic energy. When they strike the work surface, they transfer their energy quickly causing surface work. This effect is smaller than hammering.

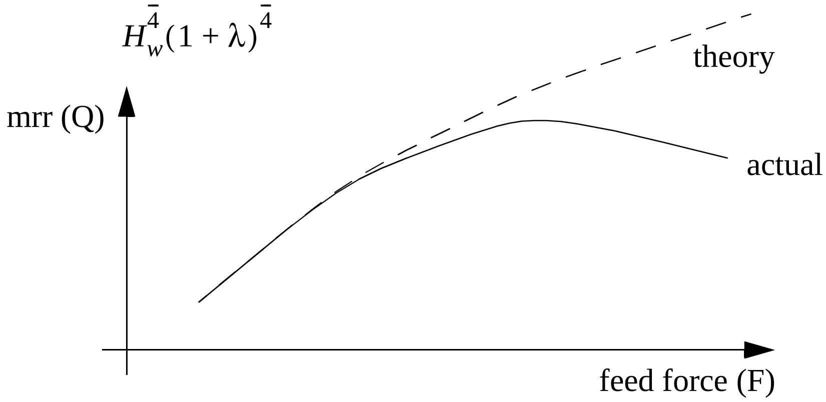
- The grains are not actually perfectly spherical, and as a result smaller rounds actually lead to faster machining.

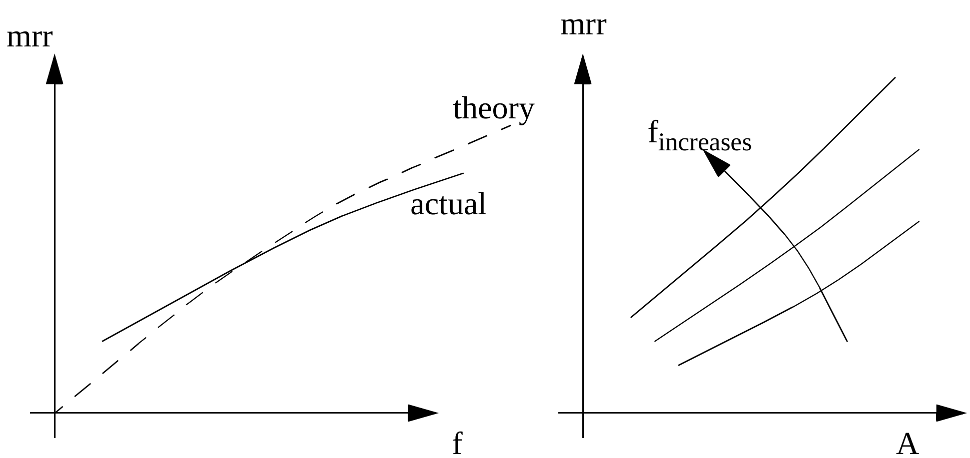


we can
approximate
d1 = d*d and
use d1 in place of
d for the
calculations
(all units in mm)

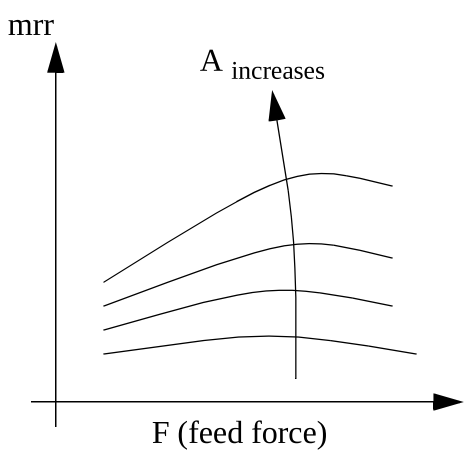
The relationship has been experimentally determined to be more like,

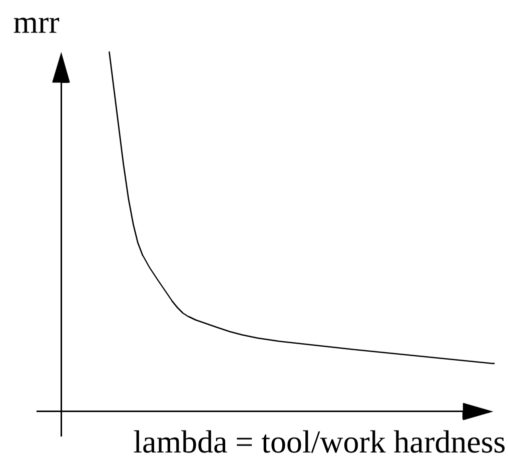
$$Q \propto \frac{dF^{\frac{3}{4}}A^{\frac{3}{4}}C^{\frac{1}{4}}}{H_w^{\frac{3}{4}}(1+\lambda)^{\frac{3}{4}}}f$$





• mmr decreases when static force F gets high enough to crush abrasive grains.

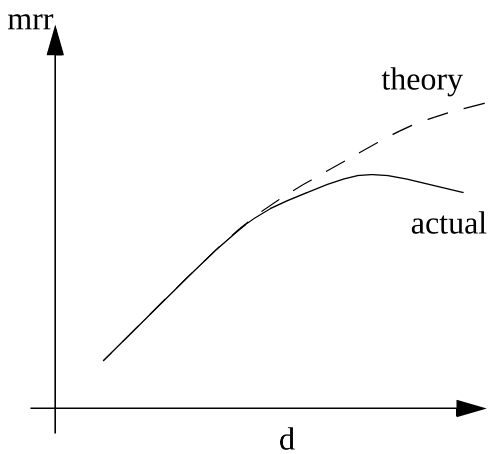


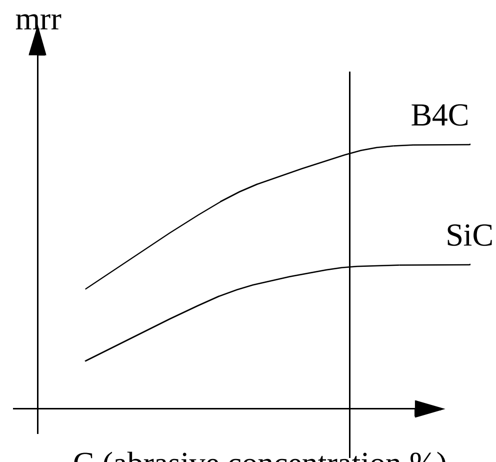


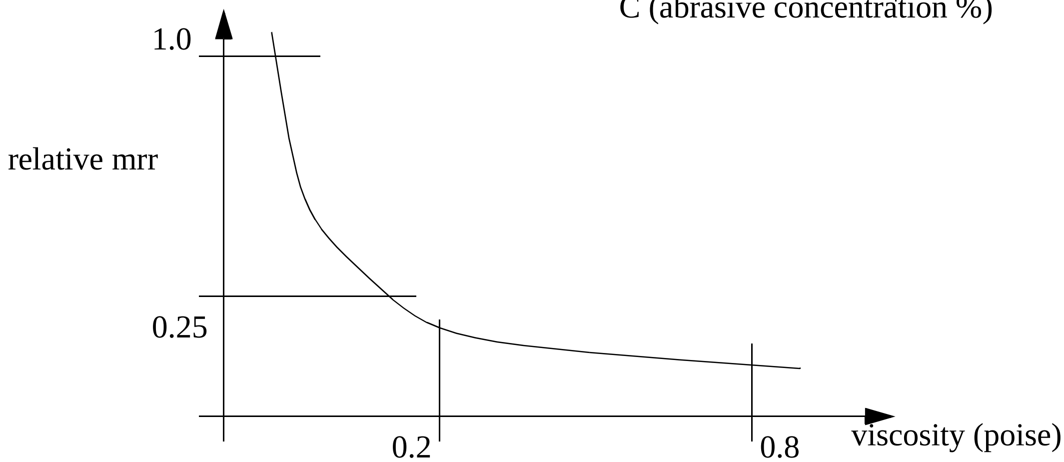
• f = 16.3 KHz, A = 12.5 micro m, grain = 100 mesh.

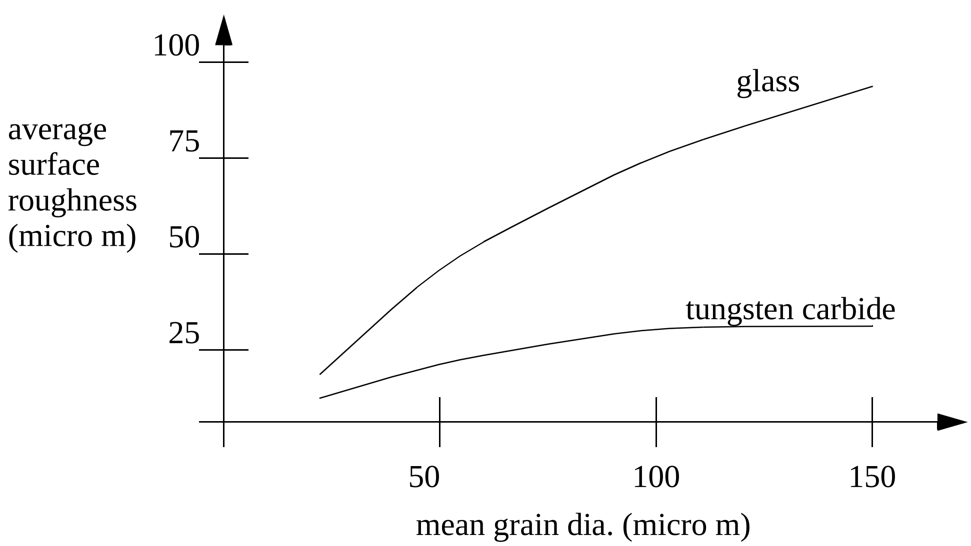
work material	relative mrr
glass	100.0
brass	6.6
tungsten	4.8
titanium	4.0
steel	3.9
chrome steel	1.4

• If d approaches A the grains start to crush.

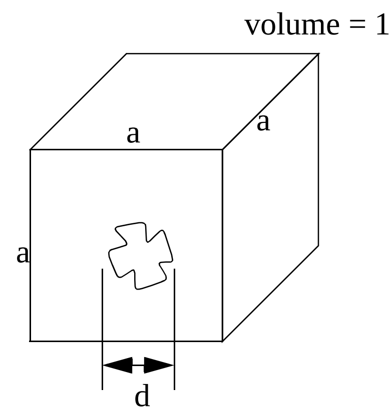








• Example - Find the machining time for a hole 5mm in diameter in a tungsten carbide plate 1cm thick. The grains are .01mm in diameter, the feed force is 3N, and the amplitude of oscillation is 20 micro m at a frequency of 25KHz. The fracture hardness is approximately 6900N/mm^2. The slurry is mixed in equal parts water and abrasive.



tool gap b = d
N cubes in contact area

$$a^3 = N\left(\frac{4}{3}\pi r^3\right)$$

Therefore,

d=.01 * 10^{-3} m
F = 3N
A = 20 * 10^{-6} m
f = 25 KHz
H_w = 6900 * 10^6 N/m^2

$$Q = \frac{2}{3}\pi(dH_w)^{\frac{3}{2}}Zf$$

$$h_w \approx \sqrt{\frac{8FA}{\pi Z d_1 H_w(1+\lambda)}}$$

We still need Z, d_1, lambda, therefore find with,

$$Z \approx \frac{1}{2}\frac{4a^2}{\pi d^2}$$ assumes a square hole

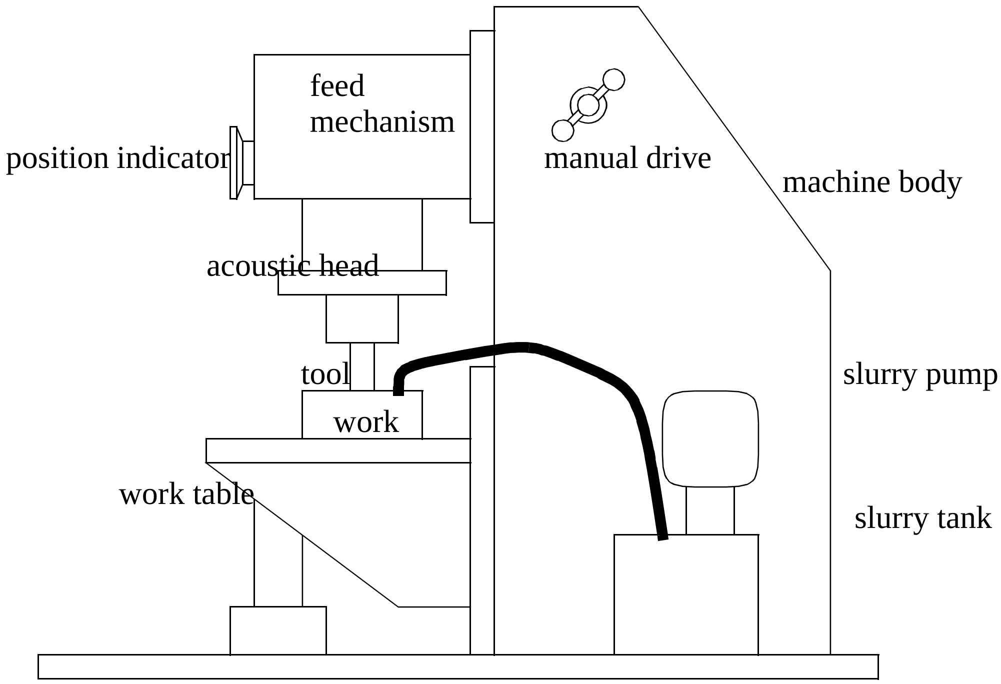
$$\lambda = \frac{H_w}{H_t} = 5(\text{assumed})$$

$$d_1 = d^2 \text{ (mm)}$$

Therefore Z = ?????, hw = ?????????, Q = ?????????? mm^3/sec
considering the volume of the hole, the required time is,

$$t = \frac{V}{Q} = \frac{\pi\left(\frac{5mm}{2}\right)^2(1cm)}{????} =$$

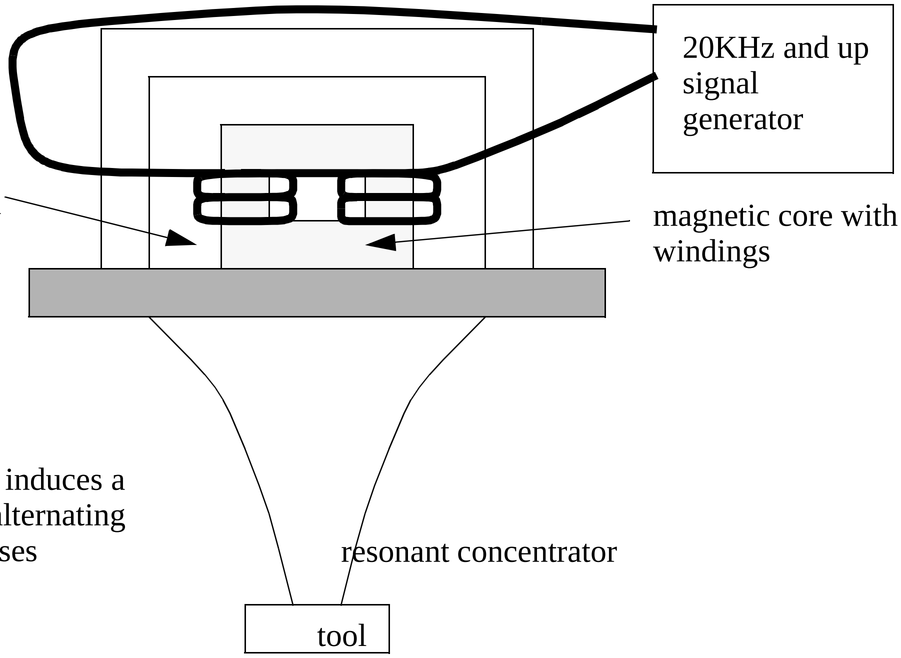
• Basic machine layout,



ultrasonic drilling machine

- The acoustic head is the most complicated part of the machine. It must provide a static force, as well as the high frequency vibration

- The magnetostrictive head is quite popular,



Basic Idea - the coil induces a vibration when the alternating magnetic filed reverses

For magnetostrictive head,

$$\lambda = \frac{c}{f} = \frac{1}{f}\sqrt{\frac{E}{\rho}}$$

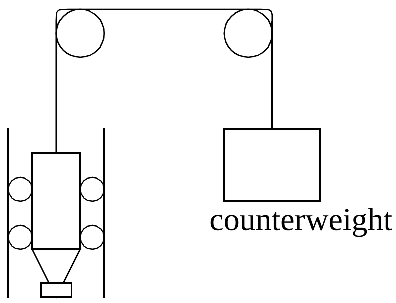
• Magnetostrictive materials should have a good coupling of magnetic and mechanical energy,

$$K_r = \sqrt{\frac{E_w}{E_m}}$$

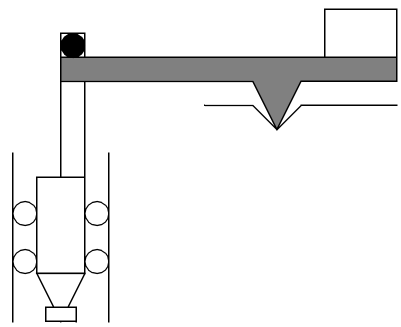
where,
Ew = mechanical energy
Em = magnetic energy

material	coeff.magnetostrictive elongation 10**6 (Ems)	coeff. of magnetomechanical elongation, Kr
Alfer (13% Al, 87% Fe)	40	0.28
Hypernik (50% Ni, 50% Fe)	25	0.20
Permalloy (40% Ni, 60% Fe)	25	0.17
Permendur (49% Co, 2% V, 49% Fe)	9	0.20

• The vibrating head is supplied with a constant force using,
  - counter weights
  - springs
  - pneumatics and hydraulics
  - motors

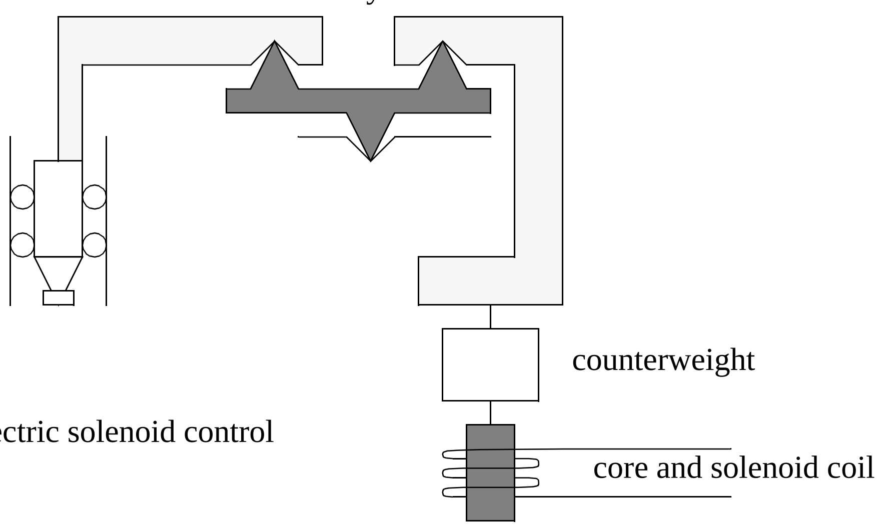


counterweight and pulley

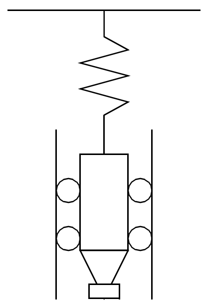


counterweight with lever and fulcrum

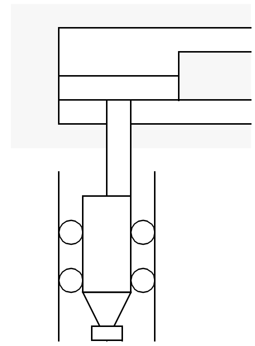
fulcrum system



electric solenoid control



spring control



hydraulic (pneumatic) control

• If a tool is designed to increase flow, better cutting speeds will occur.

• Tools
  - hard but ductile metal
  - stainless steel and low carbon
  - aluminum and brass tools wear near 5 to 10 times faster

• Abrasive Slurry
  - common types of abrasive
    - boron carbide (B_4C) good in general, but expensive
    - silicon carbide (SiC) glass, germanium, ceramics
    - corundum (Al_2O_3)
    - diamond (used for rubies, etc)
    - boron silicarbide (10% more abrasive than B_4C)
  - liquid
    - water most common
    - benzene
    - glycerol
    - oils
  - high viscosity decreases mrr
  - typical grit size is 100 to 800

• Little production of heat and stress, but may chip at exit side of hole. Sometimes glass is used on the back side for brittle materials.

• Summary of USM characteristics
  - mechanics of material removal - brittle fracture caused by impact of abrasive grains due to vibrating at high frequency
  - medium - slurry
  - abrasives: B_4C; SiC; Al_2O_3; diamond; 100-800 grit size
  - vibration freq. 15-30 KHz, amplitude 25-100 micro m

- tool material soft steel
- material/tool wear = 1.5 for WC workpiece, 100 for glass
- gap 25-40 micro m
- critical parameters - frequency, amplitude, tool material, grit size, abrasive material, feed force, slurry concentration, slurry viscosity
- material application - metals and alloys (particularly hard and brittle), semiconductors, nonmetals, e.g., glass and ceramics
- shape application - round and irregular holes, impressions
- limitations - very low mrr, tool wear, depth of holes, and cavities small.

• USM twist drilling has been done by attaching a magnetostrictive head to the spindle shelf.

57.1 REFERENCES

Ghosh, A., Manufacturing Science, Ellis Horwood Ltd., Chichester, UK, 1986.

57.1.1 General Questions

[change from 1 -7 source]

1. A cylindrical impression with a diameter of 10mm and a depth of 1mm has to be made on a tungsten carbide surface. The feed force is constant and equal to 5N. The average diameter of the grains in the abrasive slurry is 0.01mm. The tool oscillates with an amplitude of 30 micro m at 20 KHz. The slurry contains 1 part of abrasive to about 1 part of water. The fracture hardness of tungsten carbide workpiece may be taken as 7000 N/mm^2. Estimate the machining time.

2. A square through hole of 5mm by 5mm has to be drilled in a 5mm thick tungsten carbide sheet. The slurry is made of 1 part of 10 micro m radius boron carbide grains mixed with 1.5 parts of water. The feed force is 4N. The tool oscillates with an amplitude of 0.015mm at 25KHz. Assuming that only 20% of the pulses are effective, calculate the time required to complete the job.

3. In an ECM operation, a pure copper block is being machined. If a current of 5000A is used, determine the volume rate of material removal from the copper block.

4. The composition of a Nimonic alloy turbine blade is 18% cobalt, 62% Ni, and 20% chromium. It is being machined electrochemically with a current of 1500A. Find out the volume removal

rate if the density of the alloy is 8.3g/cm^3. The dissolution valency of chromium is 6, whereas that for both nickel and cobalt is 2.

5. The composition of a monel alloy workpiece undergoing electrochemical machining is as given here:

63% Ni, 31.7% Cu, 2.5% Fe, 2% Mn, 0.5% Si, 0.3% C

if the machining current is 1000A, estimate the volume removal rate.

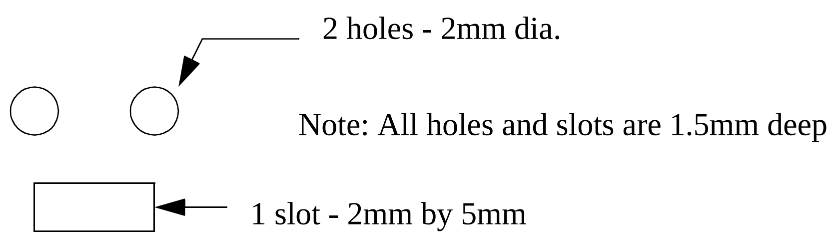
6. The equilibrium gap when machining (electrochemically) iron, using NaCl solution in water as the electrolyte, is found to be 0.2mm. The current density is 200A/cm^2, the operating voltage being 12V. Iron dissolves at a valency 2, the density of iron is 7.8 g/cm^3, and the specific resistance of the electrolyte is 2.8 ohm cm. Calculate the metal removal rate/unit work surface area. The overvoltage may be taken as 1.5V

7. In an electrochemical trepanning operation on a flat iron surface, an electrode in the form of a tube (with an outer diameter of 1cm). A laser beam with a power intensity of 2 * 10^5 W/mm^2 is used to drill a 0.2mm diameter hole in a tungsten sheet of 0.4mm thickness. If the efficiency of the operation is only 10%, estimate the time required.

8. TRUE / FALSE - Water is the main cutting tool in Ultra Sonic machining.

9. Why are the vibrations in USM so small?

10. USM will be used to add the following pattern to an object, If the tool is Tungsten carbide, and



the work is Cu, with an amplitude of oscillation of 10 µm, at 30KHz, how long will the operation take? (Note: the grain diameter is 20µm, and the head has a static force of 6N)

11. When is the abrasive added into the flow for the various abrasive jet machining processes?

12. Why is the depth of material removed by abrasive jet machining so variable?

13. Describe the ability of the abrasive processes to produce sharp corners.

58. ELECTRIC DISCHARGE MACHINING (EDM)

• Physical Principle,
1. charge up an electrode
2. bring the electrode near a metal workpiece (oppositely charged).
3. as the two conductors get close enough a spark will arc across a dielectric fluid. This spark will “burn” a small hole in the electrode and workpiece.
4. continue steps 1-3 until a hole the shape of the electrode is formed.

• The process is based on melting temperature, not hardness, so some very hard materials can be machined this way.

• The arc that jumps heats the metal, and about 1 to 10% of the molten metal goes into the fluid. The melted then recast layer is about 1 to 30 micro m thick, and is generally hard and rough.

• typical electrode materials are,
- copper,
- tungsten
- graphite

• The user can select the following parameters
- Electrode material
- Electrode polarity +/-
- pulse current If (A)
- pulse duration ti (micro s)
- pulse off time to (micro s)
- average voltage U (V)
- Average current I (A)
- working current density Id (A/cm2)
- open gap voltage Vo (V)
- Dielectric
- flushing mode

• These in turn effect,
- metal removal rate Vw (mm3/min)
- relative electrode wear theta (% or a fraction)

electrode metal removal rate

$$\theta = \frac{V_E}{V_w}(100\%)$$

- surface finish R (peak to valley micro m)
- thickness of recast layer
- gap between electrode and workpiece
- corner and edge radii

- Fluid
    - fluid is used to act as a dielectric, and to help carry away debris.
    - if the fluid is pumped through and out the end of the electrode, particles will push out, and mainly collect at the edges. They will lower the dielectric resistance, resulting in more arcs. As a result the holes will be conical.
    - if fluid is vacuum pumped into the electrode tip, straight holes will result.
    - quite often kerosene-based oil.

- The electrode workpiece gap is in the range of <10 micro m to <100 micro m.

- Uses a voltage discharge of 60 to 300 V to give a transient arc lasting from 0.1 micro s to 8 ms.

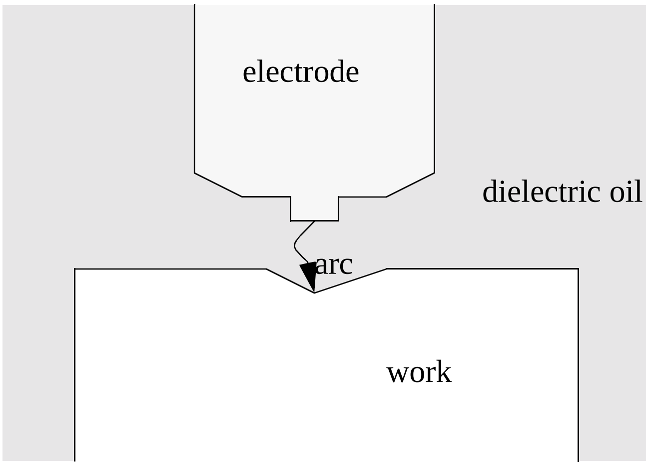
- Typical cycle time is 20 ms or less, up to millions of cycles may be required for completion of the part.

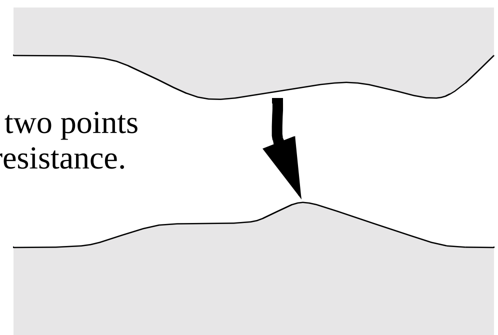
- Electrode materials are high temperature, but easy to machine, thus allowing easy manufacture of complex shapes.

- When the energy density is higher (machining faster), the results are,
    - energy density (lower to higher)
    - amount machined (less to more)
    - machining speed (slower to faster)
    - clearance (less to more)
    - surface roughness (fine to rough)

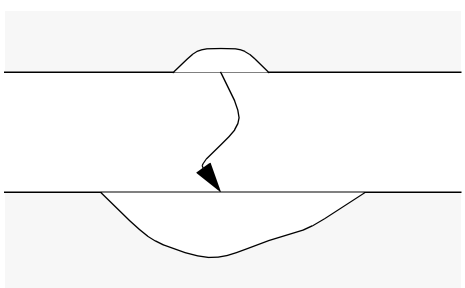
- Keep in mind the power is given by P=V I t

- Basic process,

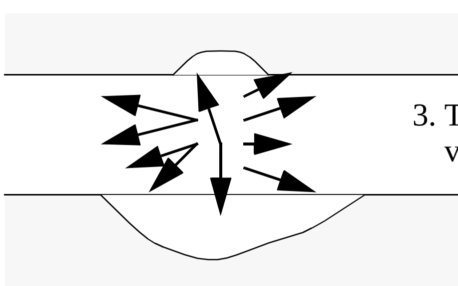




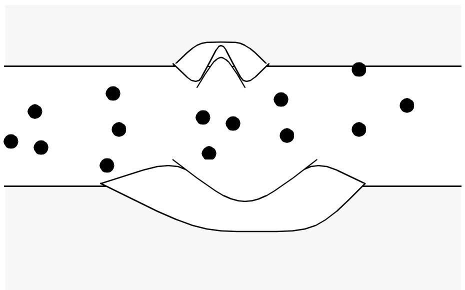
1. An arc jumps between two points along the path of least resistance.



2. The energy of the arc is so concentrated that it causes the electrode, and the work to melt. But the electrode material is chosen so that it melts less.



3. The metal and dielectric fluid are partly vaporized, causing sudden expansion.



4. The blast from the expanding vapors knocks some molten particles loose, and the remaining molten metal hardens.

• Rotating the wire in an orbital direction will,
  - increase accuracy in form and surface finish
  - decrease electrode wear

• Typical machine parameters are,

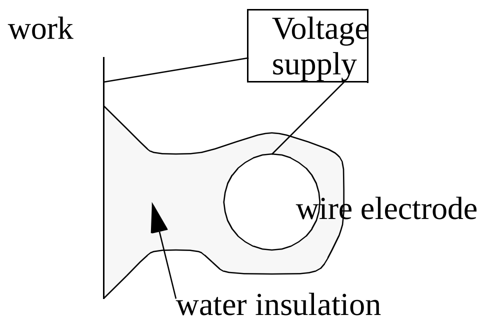
PARAMETER	TYPICAL VALUE
power (KW)	0.5-1.5
in.**3/hr.	.18-1.1
electrode wear (%)	1-10
surface (micro in. RMS)	12

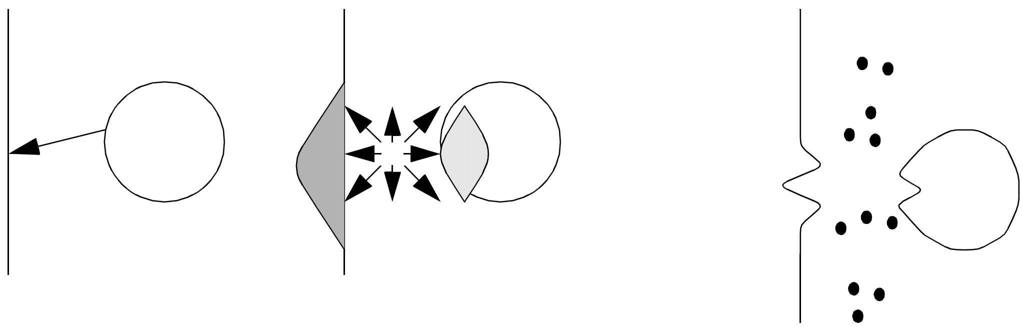
58.1 WIRE EDM

• A thin wire of brass, tungsten, or copper is used as an electrode.

• Deionized water is used as the dielectric.

• The process is similar to standard EDM,





• Slowly cuts groove in shape of wire.

• Wire is consumed and is slowly fed.

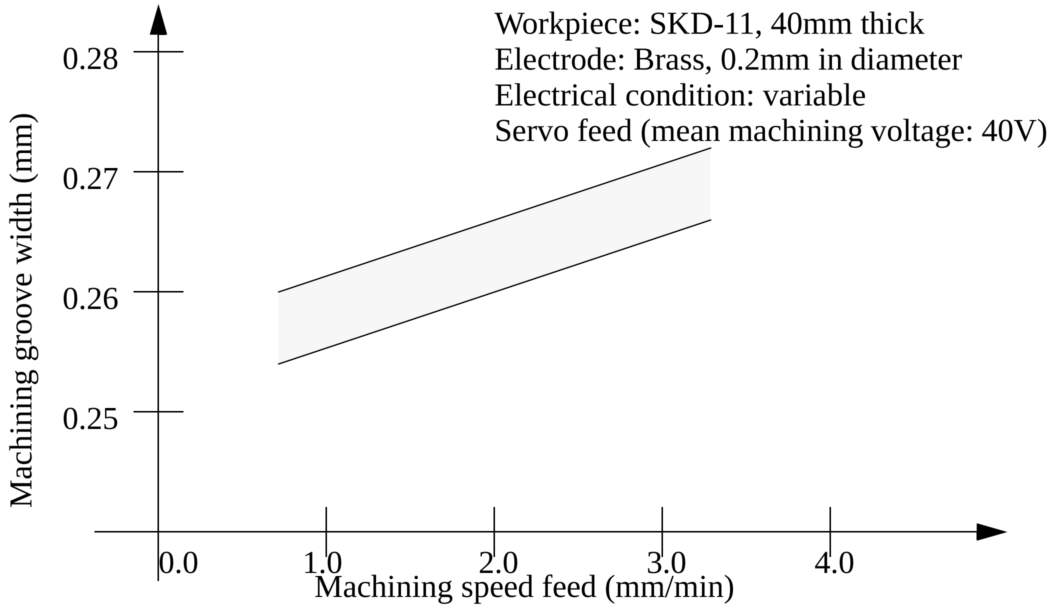
• This process is much faster than electrode EDM .

• Machine speed is,

machine speed (mm2/min)=machine speed feed (mm/min) * workpiece thickness (mm)

• Higher currents, and lower rest times increase the speed of this process.

• Relations between groove width and speed are shown in the graph below.



Relation between machining groove width and machining feed speed in wire electrode discharge machining

• This process is well suited to production of dies for plastic molding, progressive dies, etc.

• Summary of EDM characteristics,
- mechanics of material removal - melting and evaporation aided by cavitation
- medium - dielectric fluid
- tool materials - Cu, Brass, Cu-W alloy, Ag-W alloy, graphite
- material/tool wear = 0.1 to 10
- gap = 10 to 125 micro m
- maximum mrr = $5*10^3$ mm^3/min
- specific power consumption 1.8 W/mm^3/min
- critical parameters - voltage, capacitance, spark gap, dielectric circulation, melting temperature
- materials application - all conducting metals and alloys
- shape application - blind complex cavities, microholes for nozzles, through cutting of non-circular holes, narrow slots
- limitations - high specific energy consumption (about 50 times that in conventional machining); when forced circulation of dielectric is not possible, removal rate is quite low; surface tends to be rough for larger removal rates; not applicable to non-conducting materials

58.2 PRACTICE PROBLEMS

1. We try an EDM process where the copper tool has a mass of 200g before beginning and 180g after. The iron workpiece drops from 3.125kg to 3.096kg, but has rounded corners.

    a) What is the tool wear factor?
    b) If the tool was cylindrical to begin with, draw sketches of the electrode before and after.

2. What are the selection criteria for choosing between machining and EDM?

ans. EDM is particularly useful when dealing with internal cuts that are hard to get tools into. Machining tends to work best with external cuts. EDM is suitable for removal of smaller amounts of material at a much slower rate.

58.3 REFERENCES

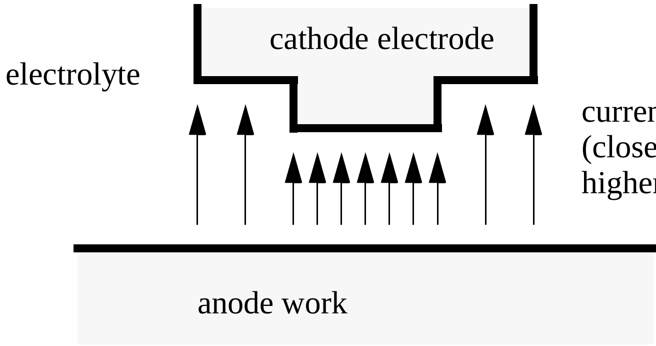
Ghosh, A., Manufacturing Science, Ellis Horwood Ltd., Chichester, UK, 1986.

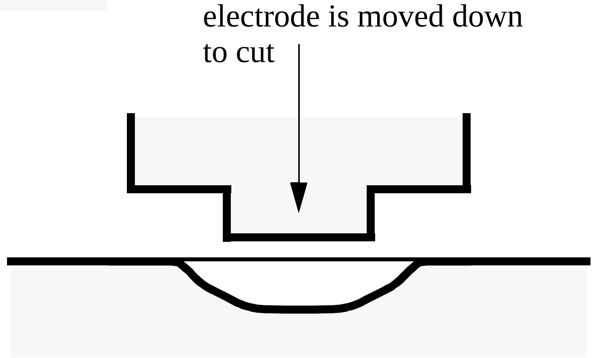
Lascoe, O.D., Handbook of Fabrication Processes, American Society of Materials, Metals Park, Ohio, 1988.

59. ELECTROCHEMICAL MACHINING (ECM)

• The physics - an electrode and workpiece (conductor) are placed in an electrolyte, and a potential voltage is applied. On the anode (+ve) side the metal molecules ionize (lose electrons) break free of the workpiece, and travel through the electrolyte to the electrode (a cathode; has a -ve charge; a surplus of electrons).

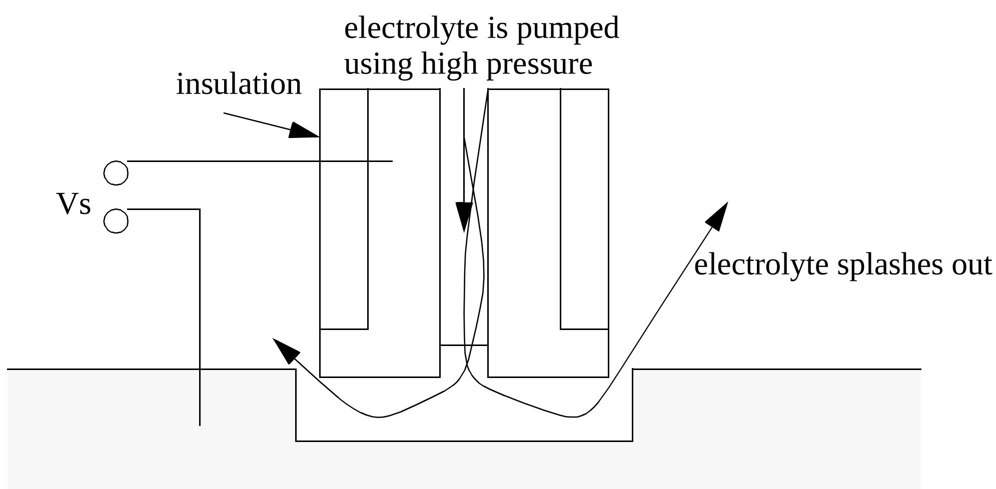
• NOTE: in EDM an arc was used to heat metal, here the metal dissolves chemically.





• Variation in the current density will result in work taking the electrodes shape.

• The electrode is fed with a constant velocity, and the electrolyte is fed through the tool. The tool is designed to eliminate deposition of the ionized metal on the electrode.



• Supply V = 8 to 20V, I = >1000A.

• Electrode gap is typically 0.1 to 0.2 mm.

• mrr is about 1600mm^3/min. per 1000A, OR 3KWhr for 16000 mm^3 (not very efficient, 30 times more than standard machining techniques).

• mrr is independent of material hardness.

• Good for low machinability, or complicated shapes.

• Very little tool wear,

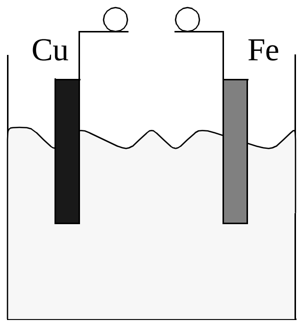
• Forces are large with this method because of fluid pumping forces.

• Faraday's laws state that,

$$m = \frac{It\varepsilon}{F}$$

m = weight (g) of a material
I = current (A)
t = time (sec)
ε = gram equivalent weight of the material
F = constant of proportionality - Faraday (96,500 coulombs)

• The basic principle is shown below



could be a battery, or electroplating, or ECM bath

NaCl + H_2O electrolyte

• The chemical reaction between an electrode and the electrolyte leads to electrons being added, or removed from the electrode metal. This addition/subtraction leads to a voltage potential.

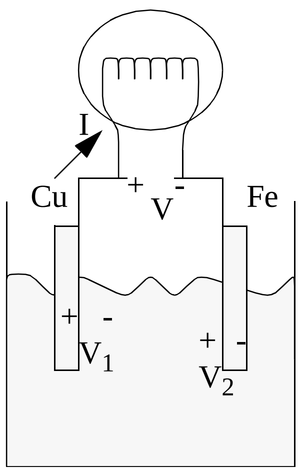
For Iron

$Fe \Leftrightarrow Fe^{2+} + 2e^{-}$ $\quad V_2 = -0.409V$

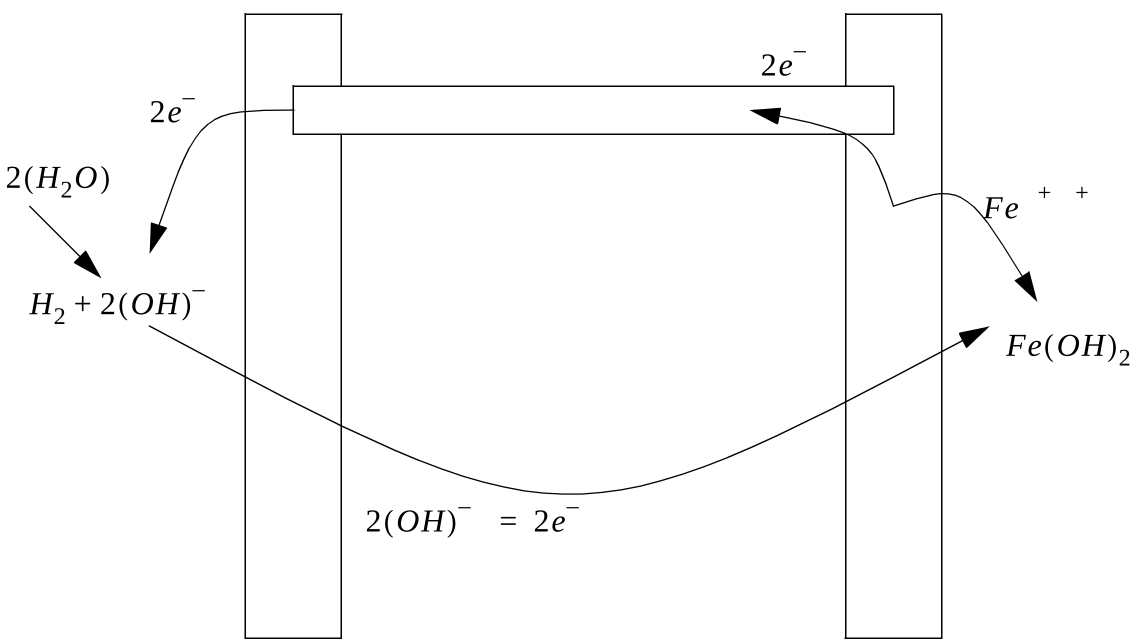
For Copper

$Cu \Leftrightarrow Cu^{2+} + 2e^{-}$ $\quad V_1 = 0.304V$

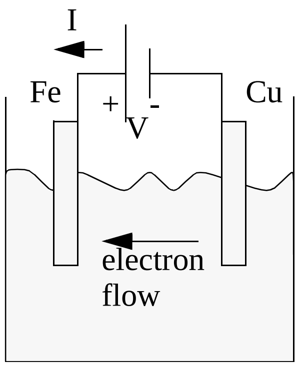
• To make a battery.



V = V$_1$ - V$_2$
V = 0.304V - (-0.409V) = 0.713V



• To do electrolysis.



In the iron (anode) - the iron dissolves, and 2 electrons are pulled out by the battery.

$$Fe \rightarrow Fe^{++} + 2e^{-}$$

In the copper (cathode) - extra electrons are pushed in by the battery and they go to the electrolyte. The electrons liberate hydrogen gas, and create a base.

$$2e + 2H_2O \rightarrow H_2 + 2(OH)^{-}$$

hydroxides, and the radical iron react to create an insoluble precipitate that falls to the bottom.

$$Fe^{++} + 2(OH)^{-} \rightarrow Fe(OH)_2$$

The electrodes and electrolyte are chosen so that deposition does not occur at either electrode. (In electrolysis we would want deposition at one of the electrodes.)

• The mrr is,

$$Q = \frac{AI}{\rho ZF}\left(\frac{cm^3}{\sec}\right) = \underbrace{\frac{0.1035\times 10^{-2}}{\rho}\left(\frac{1}{\sum_i \frac{x_i Z_i}{A_i}}\right)\left(\frac{cm^3}{A\sec}\right)}_{\text{for alloys}}$$

• e.g.

Using ECM remove 5cm^3/min from an iron workpiece. What current is required?

$$Q = 5\frac{cm^3}{min} = 5\frac{cm^3}{min}\left(\frac{1min}{60\sec}\right) = \frac{5}{60}\frac{cm^3}{\sec}$$

$$I = ?$$

$$A = 56g \text{ (periodic table)}$$

$$\rho = 7.8\frac{g}{cm^3} \text{ (from handbook)}$$

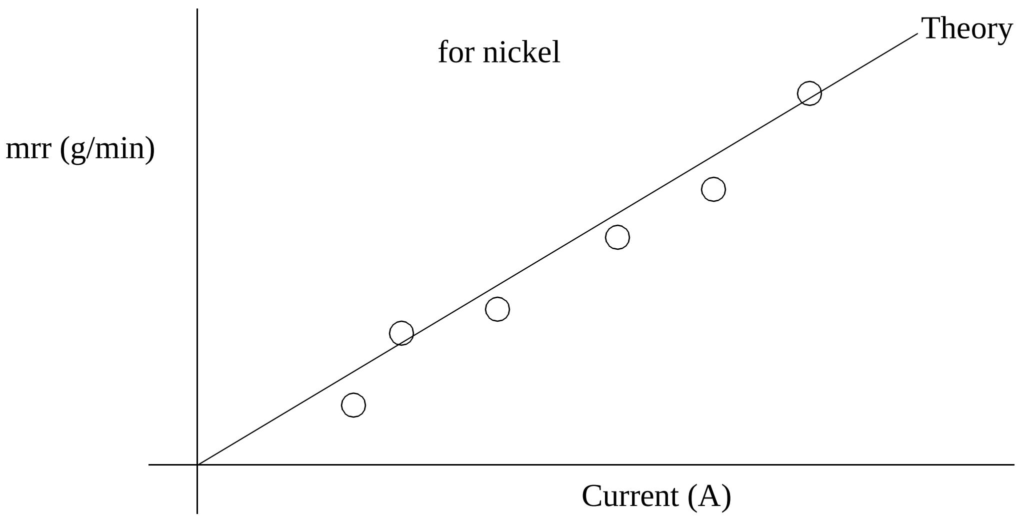
$$Z = 2 \text{ (from chemical reaction)}$$

$$F = 96,500 \text{ coulombs}$$

$$\therefore\frac{5}{60} = \frac{56I}{7.8(2)(96,500)}$$

$$I = 2240A$$

• Actual rates may vary from theory as other factors come into effect.



This can be caused by other chemical reactions also taking place.
e.g. production of Fe^{3+} instead of Fe^{2+} ions can result when a larger current or different electrolyte is used.

• The table below shows various materials and relevant properties,

metal	gram atomic weight	valency of dissolution	density (g/cm^3)
aluminum	26.97	3	2.67
chromium	51.99	2/3/6	7.19
cobalt	58.93	2/3	8.85
copper	63.57	1/2	8.96
iron	55.85	2/3	7.86
nickel	58.71	2/3	8.90
tin	118.69	2/4	7.30
titanium	47.9	3/4	4.51
tungsten	183.85	6/8	19.3
zinc	65.37	2	7.13
silicon	28.09	4	2.33
manganese	54.94	2/4/6/7	7.43
carbon		2/4	1.8-2.1

• e.g.

The composition of the Nimonic 75 alloy is given below.
Find the mmr for a current of 1000A.

%	component
72.5	Ni
19.5	Cr
5.0	Fe
0.4	Ti
1.0	Si
1.0	Mn
0.6	Cu

$$Q = \frac{0.1035\times10^{-2}}{\rho}\left(\frac{1}{\sum_i\left(\frac{x_i Z_i}{A_i}\right)}\right)$$

$$\rho = \frac{100}{\sum_i\left(\frac{x_i}{\rho_i}\right)} = \frac{100}{\frac{72.5}{8.9}+\frac{19.5}{7.19}+\frac{5.0}{7.86}+\frac{0.4}{4.51}+\frac{1}{2.33}+\frac{1}{7.43}+\frac{0.6}{8.96}} = 8.18\frac{g}{cm^3}$$

$$Q = \frac{0.1035\times10^{-2}}{8.18}\left(\frac{1}{\frac{(72.5)2}{58.71}+\frac{(19.5)2}{51.99}+\frac{(5)2}{55.85}+\frac{(0.4)3}{47.9}+\frac{(1)4}{28.09}+\frac{(1)2}{54.94}+\frac{(0.6)1}{63.57}}\right)$$

$$Q = 0.35\times10^{-4}\frac{cm^3}{A\sec}$$

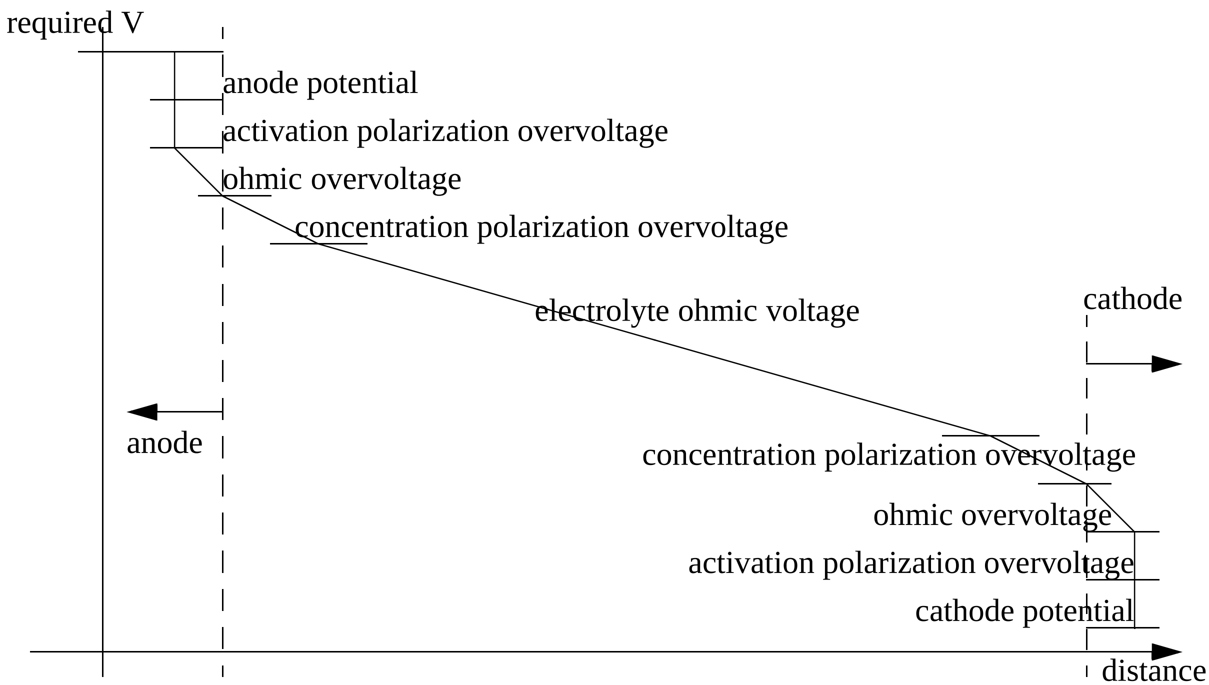
therefore, for 1 min, and 1000A

$$= 0.35\times10^{-4}(1000)(60) = 2.1\frac{cm^3}{min}$$

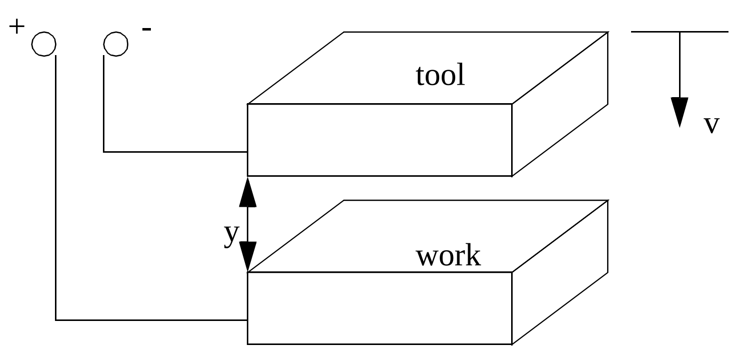
- While the current required is related to the metal removed, the voltage required depends upon,
  - electrode potential.
  - the current flow in and about the electrodes will disturb the normal distribution of voltage. Extra potential is required to overcome the effects.
  - Ion collect near electrodes and impede ion transfer from the electrode to the electrolyte, also adding a potential.
  - Some solid film forms on the surface of the electrode, also increasing resistance.
  - electrolyte resistance,

$$I = \frac{V-\Delta V}{R}$$

$$\frac{1}{R} = 10 \rightarrow 1(\Omega cm)$$

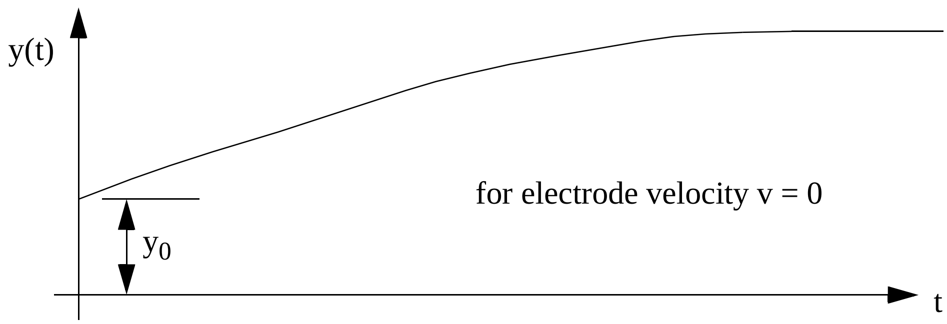


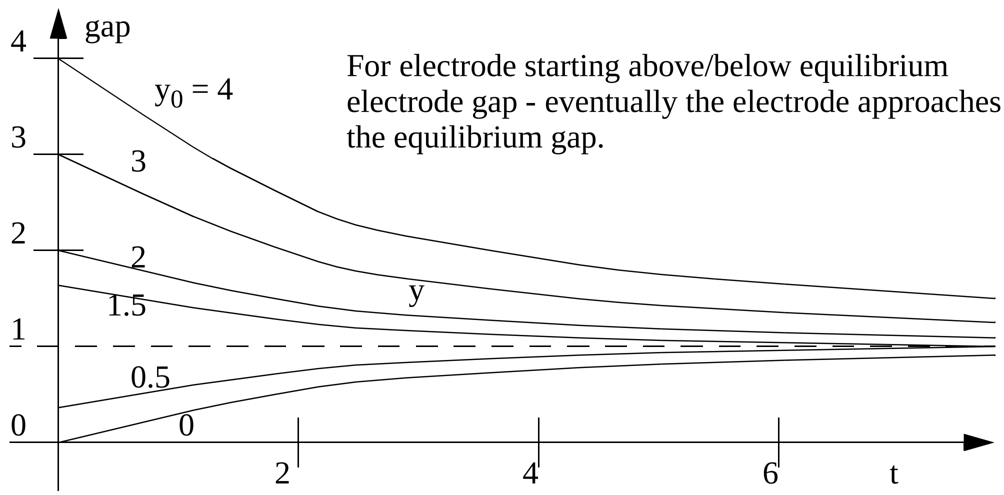
• The feed of the electrodes has the following effects



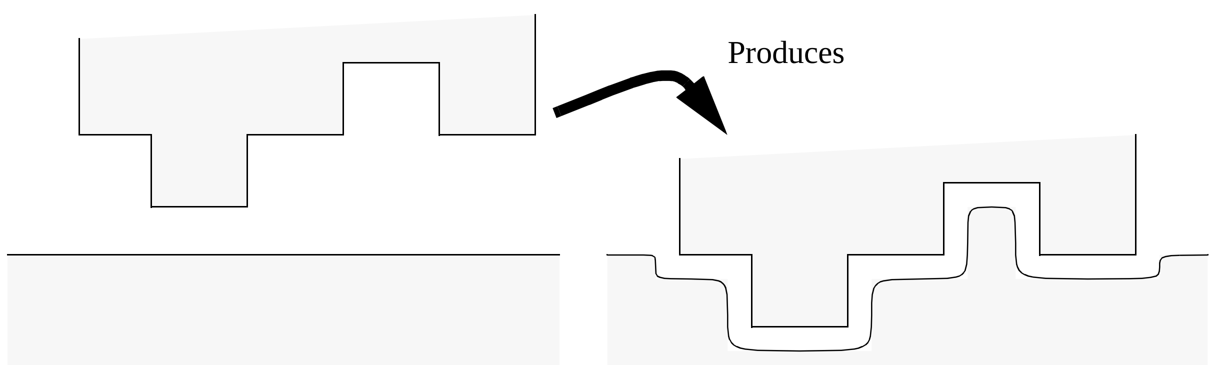
$$\frac{dy}{dt} = \left[\frac{KA(V - \Delta V)}{\rho ZF}\right]\frac{1}{y} - v$$

K = conductivity of electrolyte(Ω^{-1})





• The ECM process will erode material in a radial direction, so care must be made in tooling design.



• As current flows through the electrolyte, it is heated, and conductivity decreases.

• Surface finish is affected by,
  - selective dissolution
  - sporadic breakdown of the anodic film

- flow separation and formation of eddies
- evolution of hydrogen

• Typical electrolytes are,

Alloy	Electrolyte
Iron based	Chloride solutions in water (mostly 20% NaCl)
Ni based	HCl or mixture of brine and H_2SO_4
Ti based	10% hydroflouric acid + 10% HCl + 10% HNO_3
Co-Cr-W based	NaCl
WC based	strong alkaline solutions

• Summary of ECM characteristics,
- mechanics of material removal - electrolysis
- medium - conducting electrolyte
- tool material - Cu, brass, steel
- material/tool wear - infinite
- gap 50 to 300 μm
- maximum mrr $15*10^3$ mm^3/min
- specific power consumption 7W/mm^3/min
- critical parameters - voltage, current, feed rate, electrolyte, electrolyte conductivity
- materials application - all conducting metals and alloys
- shape application - blind complex cavities, curved surfaces, through cutting, large through cavities.
- limitations - high specific energy consumption (about 150 times that required for conventional processes), not applicable with electrically non-conducting materials and jobs with very small dimensions, expensive machines.
- surface finishes down to 25 μin.

• This technique has been combined with a metal grinding wheel in a process called Electrolytic drilling. The wheel does not touch the work, and gives a surface finish from 8 to 20 μin.

59.1 REFERENCES

Ghosh, A., Manufacturing Science, Ellis Horwood Ltd., Chichester, UK, 1986.

Krar,

59.2 PRACTICE PROBLEMS

1.

a) ECM is used to remove metal from an iron workpiece. The feature being cut is a square hole 1cm by 0.5 cm. To cut down 1cm/min, what current is generally required?

b) How would the current change if the part was 3% carbon?

c) What advantages does ECM have over EDM?

2. We have a metal alloy that is a combination of Zinc and Silicon, but we are unsure what the ratio of the metals is. But an ECM machine can cut a 5mm square hole 2mm deep at a current of ____________ in one minute. What percentage of the alloy is zinc?

3. Describe good applications for EDM.

4. Explain how EDM is best suited to producing complex internal features, such as sharp inside corners.

5. Wire EDM produces parts with a profile that is vertical. What types of applications is this well suited to? Are there particular dies that benefit from this technique?

6. A hole that is 70mm deep and 10mm in diameter. What is the machining time using a) EDM, b) ECM?

7. Which of the following materials are suitable for EDM, EBM, ECM? State Why? a) stainless steel, b) ceramics, c) quartz, d) thermoset plastic, d) copper, e) diamond.

8. Describe the ability of EDM, EBM, ECM to produce sharp corners.

9. Describe the basic operation of an EDM machine using figures. Show why corners are rounded and why flushing is important.

60. ELECTRON BEAM MACHINING

• The basic physics is an electron beam is directed towards a work piece, the electron heat and vaporize the metal.

• Typical applications are,
  - annealing
  - welding
  - metal removal

• electrons accelerated with voltages of approx. 150,000V to create velocities over 200,000 km/sec.

• beam can be focused to 10 to 200 micro m and a density of 6500 GW/mm^2

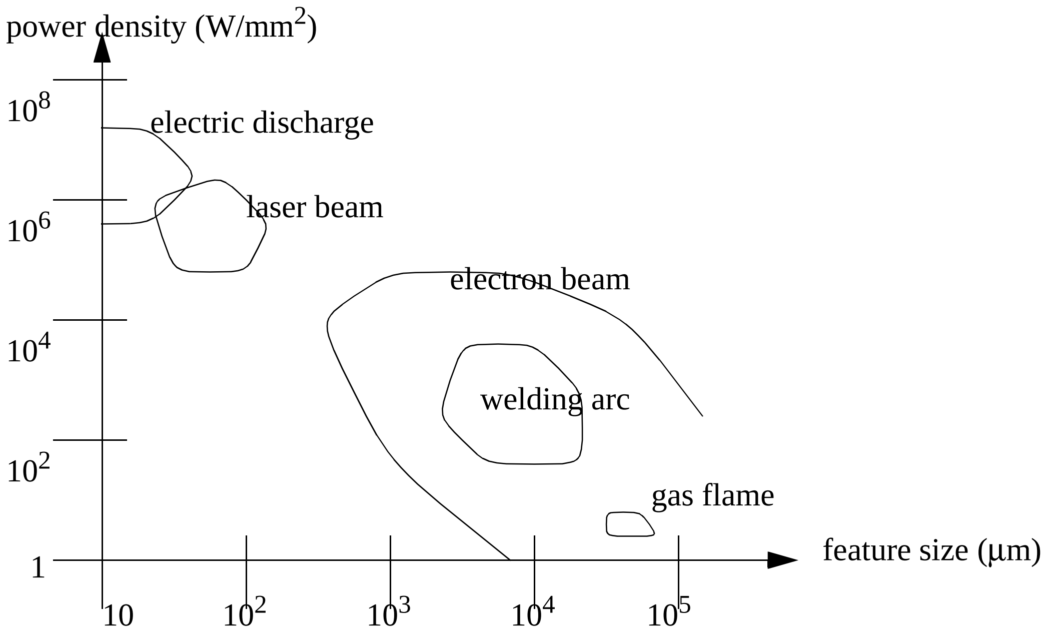
• good for narrow holes and slots.
  e.g. a hole in a sheet 1.25 mm thick up to 125 micro m diameter can be cut almost instantly with a taper of 2 to 4 degrees

• the electron beam is aimed using magnets to deflect the stream of electrons

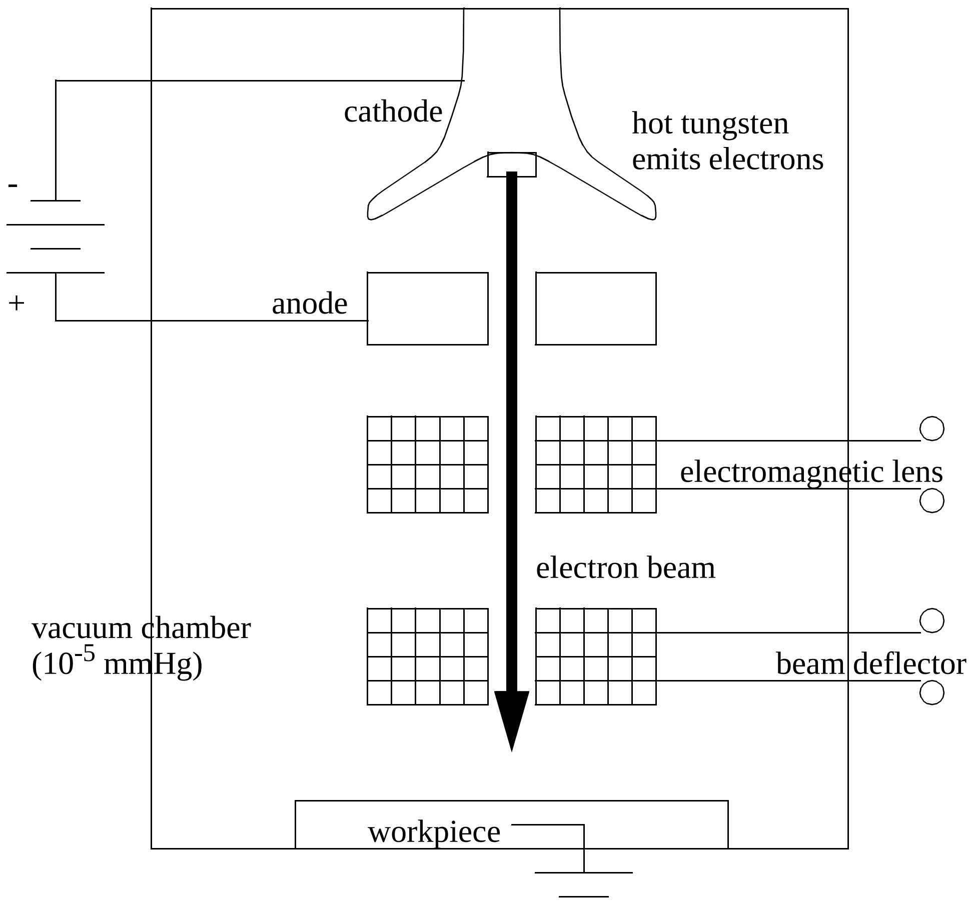
• a vacuum is used to minimize electron collision with air molecules.

• beam is focussed using an electromagnetic lens.

ASIDE: Power density available from different processes



• The process looks like,



• Some examples of cutting performance are given below,

EBM DRILLING EXAMPLES

material	workpiece thickness (mm)	Hole diameter (micro m)	Drilling time (sec)	Accelerating Voltage (KV)	Beam Current (micro A)
tungsten	0.25	25	<1	140	50
stainless steel	2.5	125	10	140	100
stainless steel	1.0	125	<1	140	100
aluminum	2.5	125	10	140	100
alumina (Al_2O_3)	0.75	300	30	125	60
Quartz	3.0	25	<1	140	10

EBM SLOT CUTTING EXAMPLES

Material	Workpiece thickness (mm)	Slot Width (micro m)	Cutting Speed (mm/min)	Accelerating Voltage (KV)	Average Beam Current (micro A)
Stainless steel	0.175	100	50	130	50
tungsten	0.05	25	125	150	30
brass	0.25	100	50	130	50
alumina	0.75	100	600	150	200

• typical energy requirements for cutting are,

Material	C ($W/mm^3/min$)
Tungsten	12
Fe	7
Ti	6
Al	4

• e.g. to cut a 150 micro m wide slot in a 1mm thick tungsten sheet, using a 5KW power source, determine the cutting speed.

- assume speed is v mm/min
- Q = 150/1000 * 1 * v mm^3/min
- beam power P = CQ = 12 (150/1000) v = 5000 therefore, v = 46 mm/sec

• Basic mechanics,

$$M_e = 9.109\times10^{-31}kg$$
$$C = 1.602\times10^{-19} \text{ coulombs}$$

electron properties

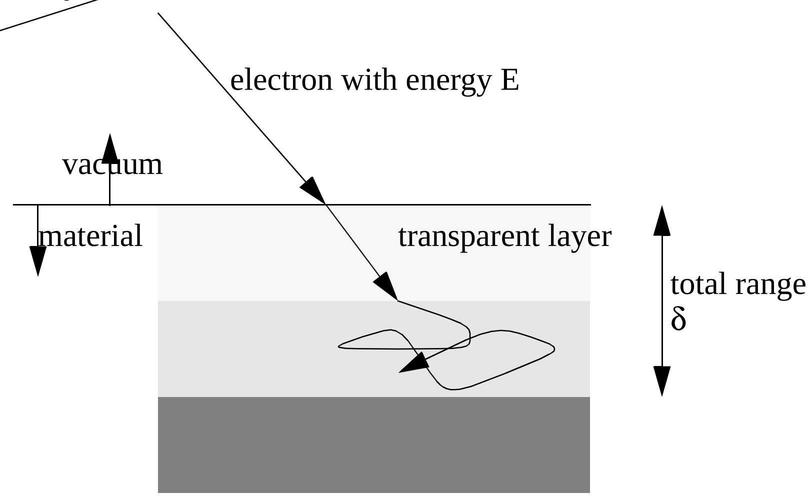
$$E = \frac{1}{2}M_e(u^2 - u_o^2)e\text{ V}$$

potential field accelerated through

electron charge

final velocity

initial velocity



the electron travels through the vacuum until it strikes the material. They generally penetrate the top layer, then become trapped in some layer beneath the surface.

$$\delta = 2.6\times10^{-17}\frac{V^2}{\rho}(mm)$$

V = Accelerating potential (V)

ρ = material density (kg/mm3)

• e.g.

When drilling steel with EBM an accelerating voltage of 150KV is used.
What is the electron range?

$$\rho = 76\times10^{-7}\left(\frac{kg}{mm^3}\right)$$

$$\delta = 2.6\times10^{-17}\left(\frac{150\times10^3}{76\times10^{-7}}\right)^2 mm = 77\mu m$$

• the heat rise can be estimated using a one dimensional heat flow equation

$$\frac{\partial\theta(z,t)}{\partial t} = \frac{\alpha\partial^2\theta(z,t)}{\partial z^2} + \frac{1}{C_p}H(z,t)$$

θ = temperature of metal

α = thermal diffusivity

z = distance from surface

t = time

C_p = specific heat of metal

ρ = metal density

$H(z,t)$ = heat source intensity

$$\therefore H(z) = Ae^{-bz}$$

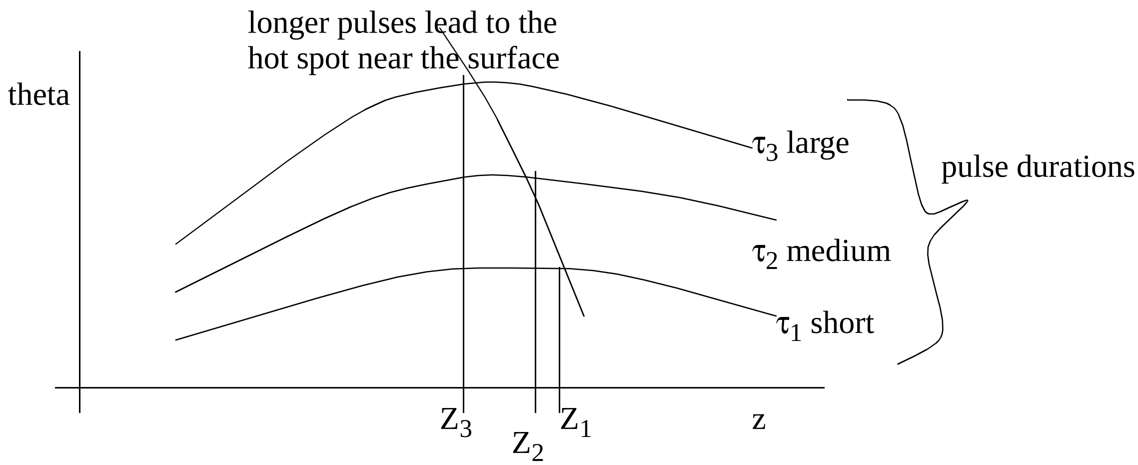
A = constant

b = constant of energy absorption by the metal

$$\therefore \frac{\partial\theta(z,t)}{\partial t} = \frac{\alpha\partial^2\theta(z,t)}{\partial z^2} + \frac{A}{\rho C_p}e^{-bz}$$

now assume,

1. the metal body is semi-infinite
2. the surface of the metal is insulated, except for the hot spot
3. the heat H(z) remains constant over time



• We can estimate the melting temperature with,

$$Z = 0.1\frac{P}{\theta_m\sqrt{kdv\rho C_p}}$$

• e.g.

In a 1mm tungsten sheet a 150 micro m wide slot is to be cut using an electron beam of 5 KW. Find the cutting speed.

for tungsten,

$$C_p = 2.71\frac{W}{cm^3C}$$

$$k = 2.15\frac{W}{cmC} \quad \text{(thermal conductivity from lookup tables)}$$

$$\theta_m = 3400C$$

$$Z = 0.1cm \text{ (plate thickness)}$$

$$d = 0.015cm \text{ (beam and slot width)}$$

$$P = 5\times10^3 W$$

$$\therefore 0.1 = \frac{5\times10^3}{3400\sqrt{2.15(0.015)v(2.71)}}$$

$$\therefore v = 24.7\frac{cm}{\sec}$$

• Other effects of EBM
  - process done in vacuum, so it is best suited to small parts, but vacuum also reduces contamination
  - very high heat concentration reduces peripheral heating of surface less that 50 micro m from the cut the part is at room temperature.

• Summary of EBM characteristics,
  - mechanics of material removal - melting, vaporization
  - medium - vacuum
  - tool - beam of electrons moving at very high velocity
  - maximum mrr = 10 mm^3/min
  - specific power consumption = 450W/mm^3/min
  - critical parameters - accelerating voltage, beam current, beam diameter, work speed, melting temperature
  - materials application - all materials
  - shape application - drilling fine holes, cutting contours in sheets, cutting narrow slots
  - limitations - very high specific energy consumption, necessity of vacuum, expensive machine.

60.1 REFERENCES

Ghosh, A., Manufacturing Science, Ellis Horwood Ltd., Chichester, UK, 1986.

60.2 PRACTICE PROBLEMS

1.
   a) If the typical energy requirement for an EBM cut slot (0.1mm wide by 0.5mm deep) is 6(W/(mm^3/min)) for titanium, how fast can the hole be cut if a 1KW machine is used?
   b) Explain why you think the result in #5.a) is accurate/inaccurate.

61. ION IMPLANTATION

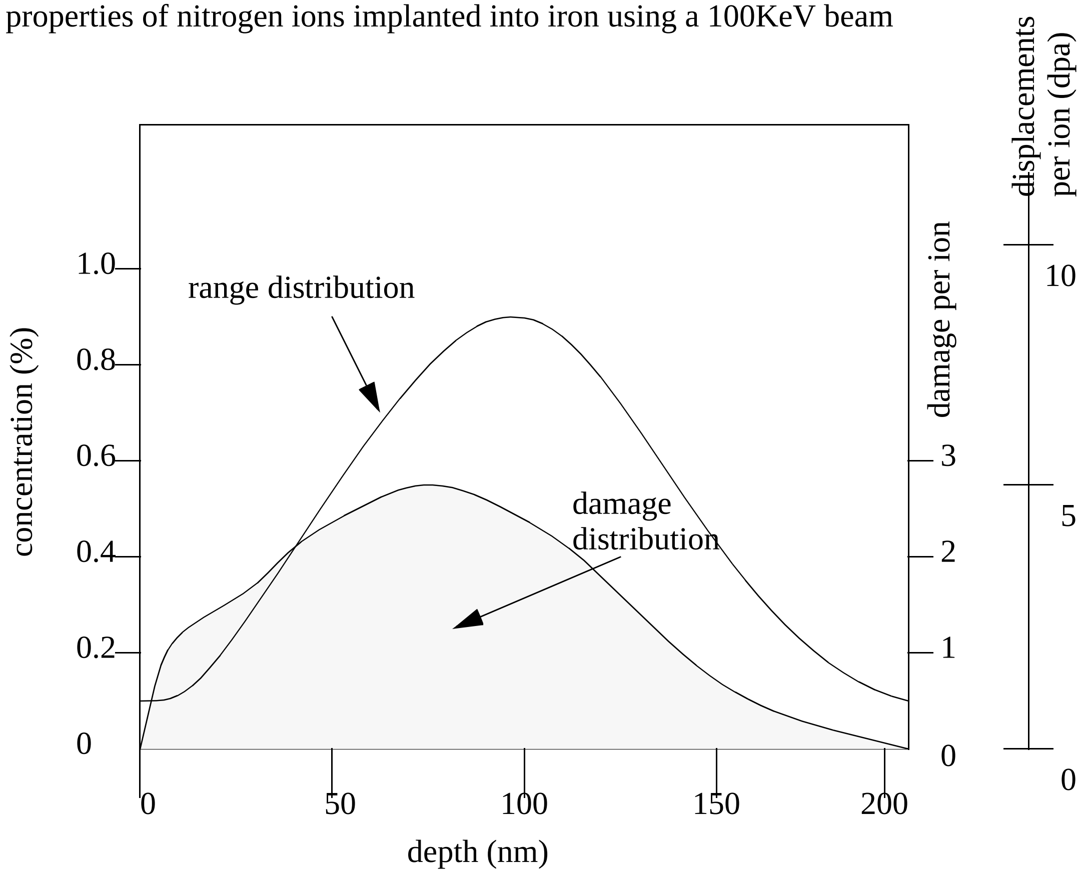
• original application was doping semiconductors with boron, arsenic, phosphorous, etc.

• Ions can be implanted with electron beams or lasers.

• Ion penetration is a result of high energy ions arriving at a surface. The penetration depth is a function of energy (10-200 KeV typically) and collisions with the target matrial lattice.

• Typical impacts, and impact depth are depicted in the figure below, [source, unknown]

The properties of nitrogen ions implanted into iron using a 100KeV beam



• Energy is dissipated in two ways,
  - excitation of electrons
  - elastic deformation of the lattice

• The beam penetration basically has a gaussian distribution about some central value.

• After the ion enters the surface it may collide with a number of atom, knocking them out of location and strain hardening the material. The ions will eventually come to rest at some depth in the material.

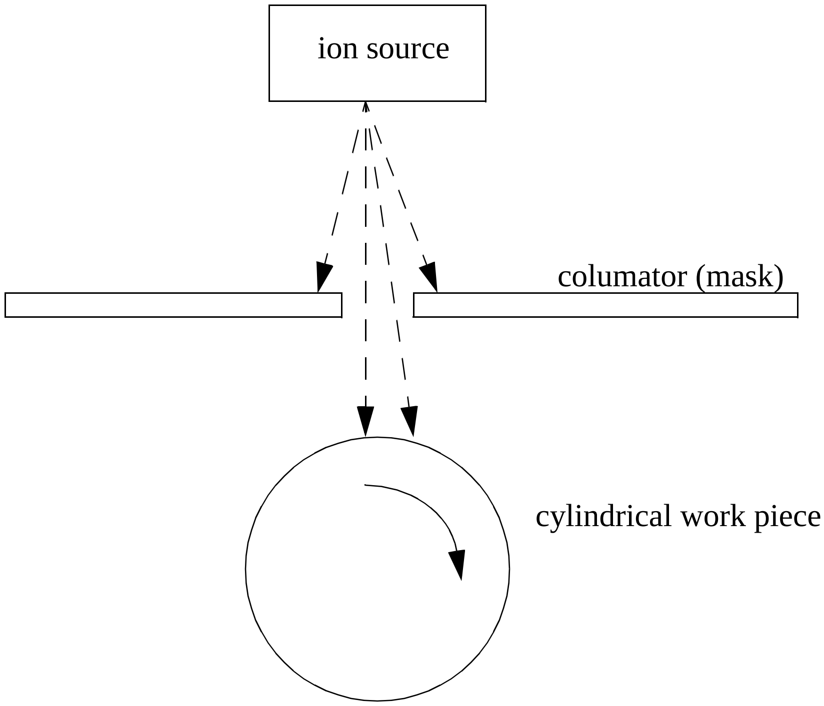
• The radiation effects causes a loss of energy as the incident ion beam strikes and displaces target atoms.

• Sputtering is the effect where incoming ions are reflected back in their direction of origin, and if energetic enough they will leave the surface.

• The cascade effect involves an ion with sufficient energy colliding with one atom, in turn causing more collisions.

• The implanted ion results in surface stress, and when concentrations are high enough, this can lead to partial deformations.

• The System,



• A columator is in use to prevent ions from striking the surface at shallow angles and sputtering.

• The workpiece is rotated to ensure good surface coverage

• One high dose source can be replaced with a number of lower dose systems.

• Advantages,
  - low temperature processing reduces handling an stress problems.
  - no dimensional changes
  - good adhesion of treated surface
  - new alloys possible
  - can improve corrosion, oxidation, wear, hardness, friction, fatigue

• Disadvantages,
  - very shallow treatment (< 1 μm)
  - high cost
  - the surface can be weakened by radiation effects

• Applications,
  - Nitrogen implantation has been used to increase wear resistance and give longer life,

    - injection molding screws
    - high speed steel tools
    - a clutch housing tool
    - hip prosthesis
  - yttrium gives oxidation and wear resistance
  - titanium and carbon on iron gives lower friction and better wear.
  - chromium is used to maintain strength of holes.

• After layers of materials have been implanted the surface can be bombarded with another ion beam that causes collisions and better mixes the implanted ions more uniformly in the surface. This technique is known as ion beam mixing.

• Ion beam enhanced deposition (IBED) uses normal surface deposition techniques and an accompanying ion beam that increases the thickness of the deposited layer, and bonding between the new layer and the existing material.

61.1 THIN LAYER DEPOSITION

• Thin layers can be mixed into surfaces using electron and laser beams,
  1. A thin layer is deposited on a surface with other techniques,
    a) electrostatic vapor deposition
    b) a thin sheet is applied
    c) the material is delivered as the beams work
  2. A laser or electron beam melts the surface and mixes the two materials

• The rates can be greater than 1 m/s

• Advantages,
  - radiation penetration is shallow
  - no chemical contamination
  - no gas or jets to disturb molten surface
  - high precision for delivery
  - automation is possible

• Disadvantages,
  - high capitol cost
  - beams narrow, so multiple passes required (slow)

61.2 PRACTICE PROBLEMS

1. TRUE / FALSE - Ion beam surface finishing is used to place material on a surface.

62. ELECTROSTATIC SPRAYING

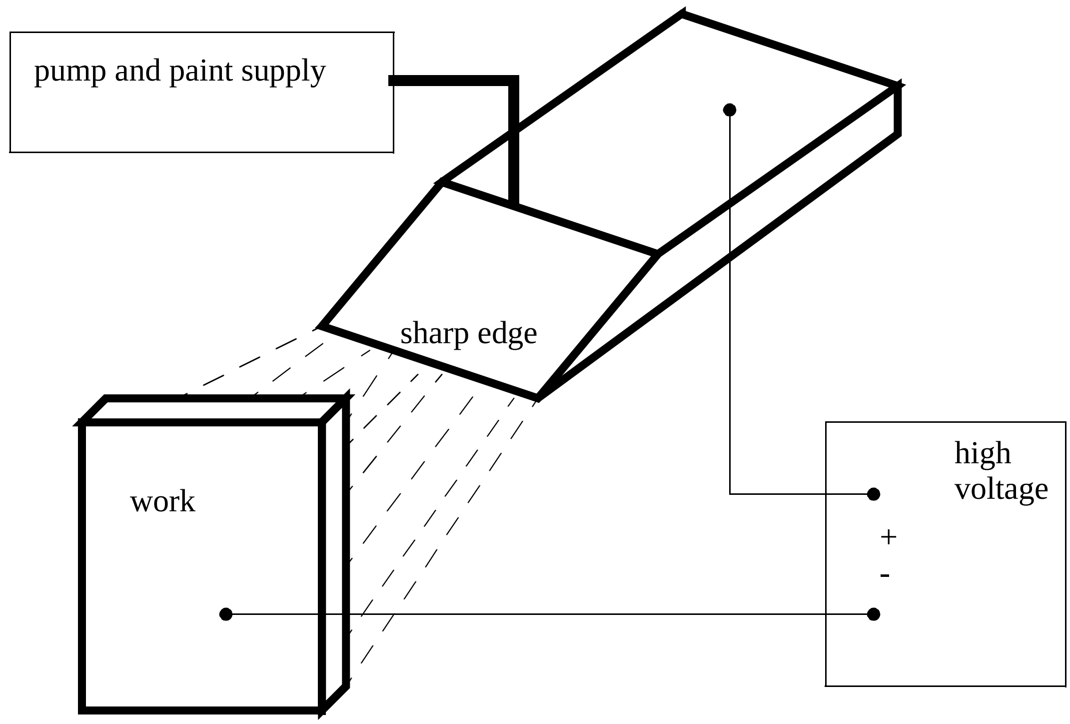
• Used to coat an object to,
  - reduce corrosion
  - protect against scratching
  - stop contact with air/water/chemicals/etc
  - alter appearance

• Electrostatic paintig methods
  - increases the production rate
  - reduces paint wastage
  - are well suited to automation
  - give good finishes

• The basic process is,
  - before/as the paint is sprayed, it is given a negative charge (extra electrons).
  - The workpiece is positively charged, thus attracting the paint particles
  - The paint is generally sprayed at the workpiece, the electrostatics even out the dispersion, and reduce wastage.

62.1 ELECTROSTATIC ATOMIZATION METHOD

• The Blade Method 9Ransburg's No. 1 process),
  - no spraygun used
  - a straight sharp edge is used charged to about 90 KV
  - the work is grounded
  - the paint is slowly pumped onto the blade, it spreads out, and by the time it reaches the tip it comes off as small charged droplets.
  - the shape of the workhead encourages a linear dispersion pattern
  - advantages,
    - high efficiency/low wastage
    - simple controls
    - suited to flat surfaces
  - disadvantages,
    - limited dispersion patterns
    - least cost effective and flexible



• The Bell Method (Ransburg's No. 2 process)
- uses a rotating bell or funnel to disperse the paint
- the bell head is about 1 ft. from the workpiece
- a potential of 90-100 KV is applied to the head while the work is grounded
- the head rotates at 900 r.p.m. to cause good paint dispersion
- advantages
    - good coverage for rounded surfaces
    - better efficiency than blade method
    - suited to spherical irregular shapes
- disadvantages,
    - extra power/equipment to run motor

• ASIDE: the edge effect in electrostatic phenomenon leads to higher concentration of charges at corners and edges.

• The Disk Method (also Ransburg's No. 2 process)
- similar to Bell method except that a flat disk is used.
- the geometry of the disk allows a much wider spray coverage
- advantages (compared to bell),
    - wider coverage area
    - well suited to irregular and long parts

• Rotating Bell handgun
  - can be used for manual/movable spraying
  - is well insulated to prevent shocks
  - well suited to complex shape because of operator aiming
  - most effecient and cost effective method

• Consider the comparative tables [source unknown],

PARAMETERS	TYPICAL VALUES
Voltage	90-100 KV
Distance between gun and work	8 to 15”
Paints	Solvent Based

• Air/Hydraulic Electrostatic Spraying
  - Type I
    - large negatively charged (100KV) electrodes are placed at the side of a spray paint line
    - work on the central conveyor is rounded,and uncharged paint is sprayed in.
    - the sprayed paint enters the electic field, becomes negatively charged and is drawn to the work.
    - can be upgraded to a full electrostatic method easily
    - a higher paint wastage results.
  - Type II
    - a typical spray gun head is modified to deposit a high voltage charge on the paint particles
    - the paint is sprayed with a negative charge, and it is attracted to a grounded work-piece
  - Type III
    - the paint is charged before passing through the spray head

• Control systems (power supplies) for spraying a resistive/non-resistive. Resistive systems use resistors to limit the maximum current that can be drawn, thus protecting the users. Non-resistive sysems require added safety precautions and are best suited to automate systems.

• The edge phenomenon can result in uneven distribution of paint near edges and corners.

• The Faraday cage effect will result in recessed areas that get less paint coverage.

• Safety issues include electrical shocks, ventillation (most paints are solvent based), and arcs from poor grounding or unexpected metal contact.

• Some automation issues are,
  - part recognition on a conveyor
  - color changes
  - booths are costly, but provide safety and process advantages

62.2 PRACTICE PROBLEMS

1. TRUE / FALSE - Parts can be electrostatically coated by dipping molds in a bath of thermo plastic powder.

2. TRUE / FALSE - Electrostatic painting uses electrical charge for better mixing of paint components.

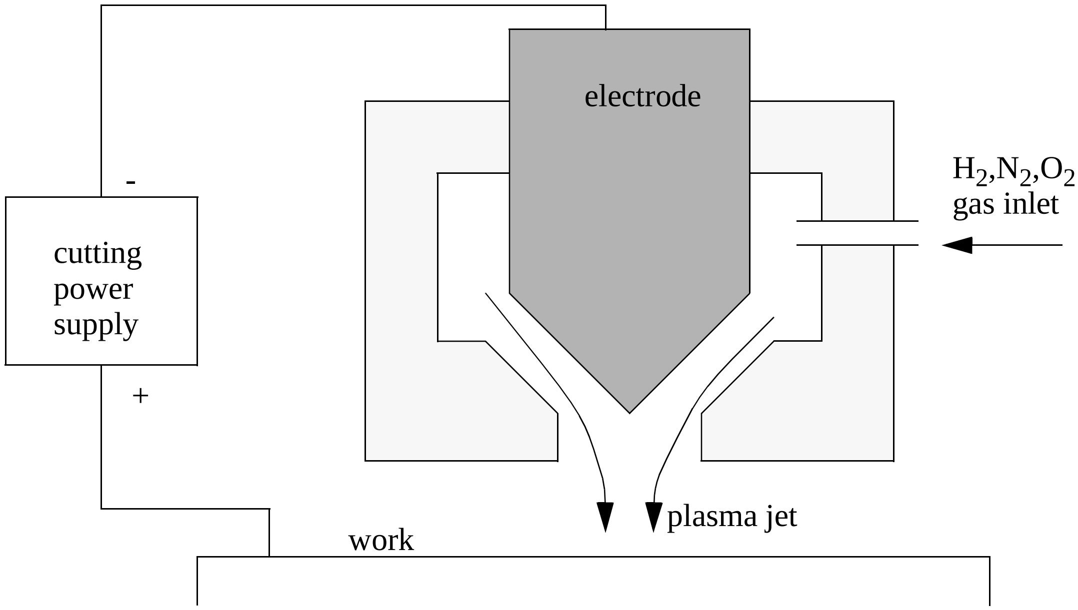
63. AIR-PLASMA CUTTING

• Basic process - uses an ionized gas jet (plasma) to cut material

• can be used on all materials that conduct electricity

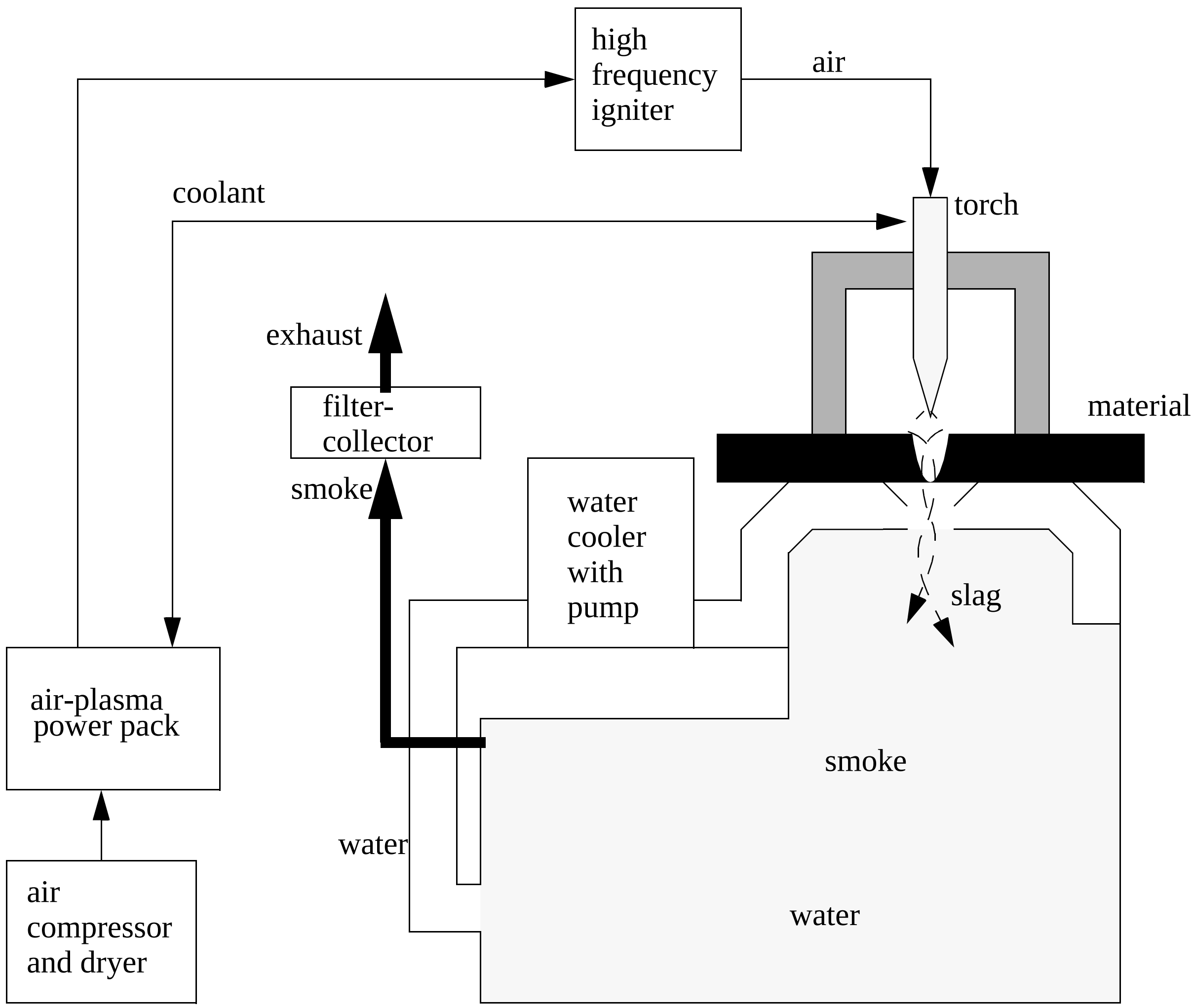
• can be used to cut materials resistant to oxy-fuel cutting,
  - stainless steel
  - monel
  - super-alloy plates

• Plasma is generated by exposing a gas stream to the electrons from an electric arc. High velocity electrons generated by the arc impact gas molecules, and ionize them.



• The gas is forced through the nozzle, and the jet heats the metal, and blasts the molten metal away.

• Advantages
    - 3 to 5 times faster than conventional gas cutting
    - can deal with any conducting material, including those not suited to normal gas cutting.
        - stainless steels
        - chromium-nickel alloys
        - aluminum
        - copper
        - etc
    - works best on ranges from .03” to 1”
    - More efficient than other types of gas plasma
    - can cut up to .15 m/sec continuously.



• Summary of Air-Plasma characteristics,

- mechanics of material removal - melting
- medium - plasma
- tool - plasma jet
- maximum temperature = 16,000C
- maximum velocity of plasma jet = 500 m/sec
- maximum mrr = 150 cm^3/min
- specific energy = 1000 W/cm^3/min
- power range = 2 to 200 KW
- maximum plate thickness = 200 mm (depends on material)
- cutting speed = 0.1 to 7.5 m/min
- voltage 30 to 250 V
- current <= 600 A
- critical parameters - voltage, current, electrode gap, gas flow rate, nozzle dimensions,

melting temperature
- materials applications - all conducting materials
- shape application - cutting plates
- limitation - low accuracy

63.1 REFERENCES

Ghosh, A., Manufacturing Science, Ellis Horwood Ltd., Chichester, UK, 1986.

Flexible Manufacturing Systems

63.2 PRACTICE PROBLEMS

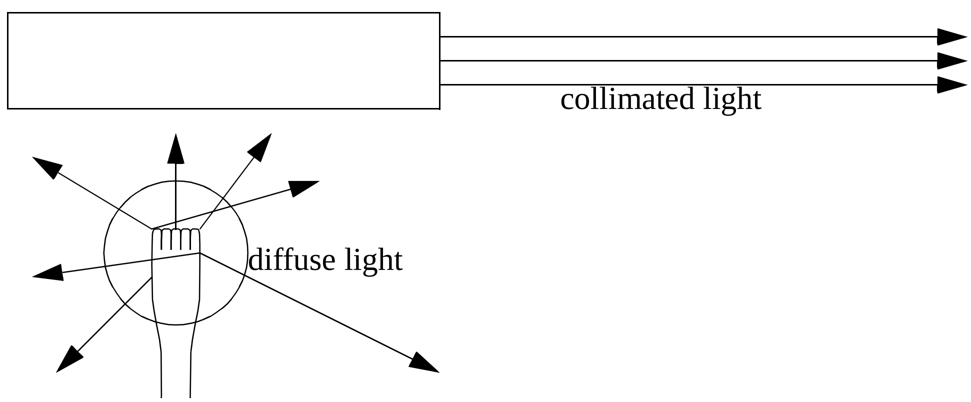
64. LASER CUTTING

64.1 LASERS

• Light Amplification by Stimulated Emission of Radiation.

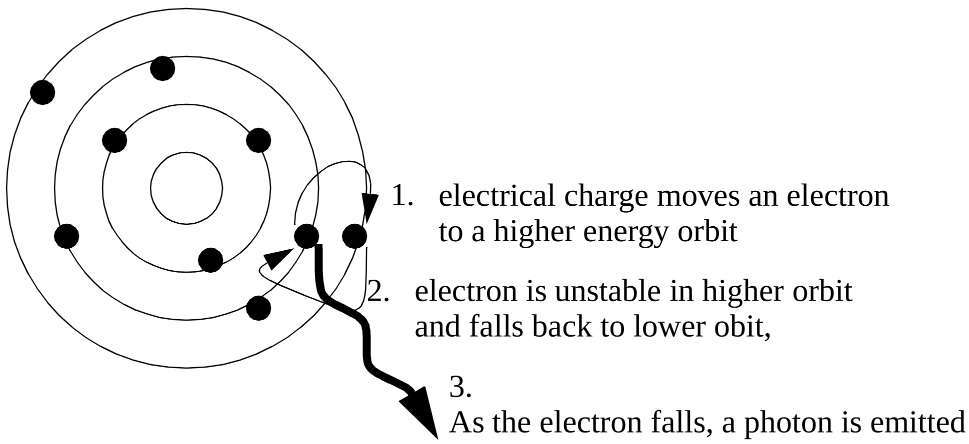
• When are they best used?
- when highly focussed energy is required (light or heat)
- when contact forces must be eliminated
- when a small geometry is required

• What do LASERs do?
- Produce collimated light - all of the light rays are (nearly) parallel. This means the light doesn't diffuse quickly like normal light.

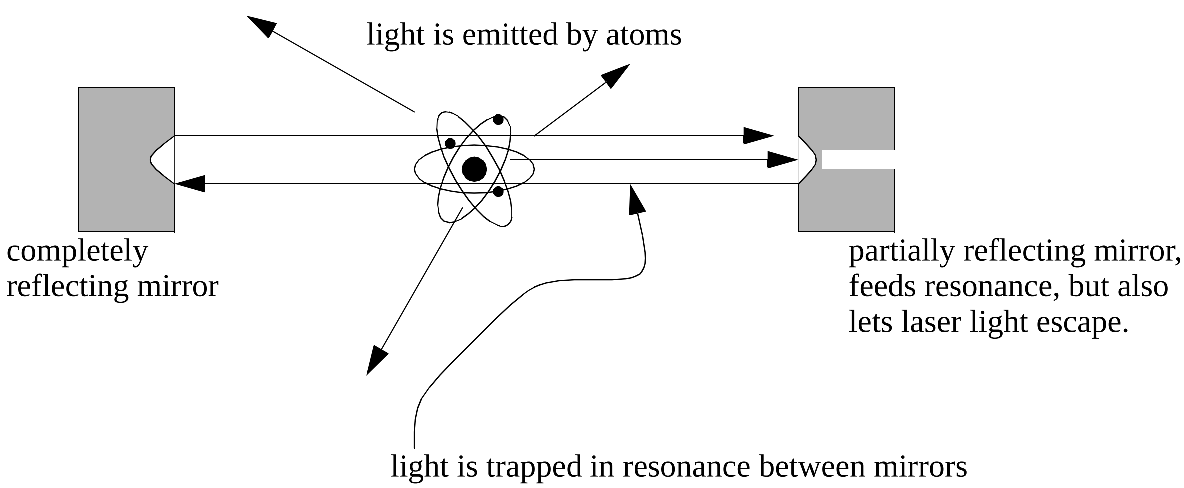


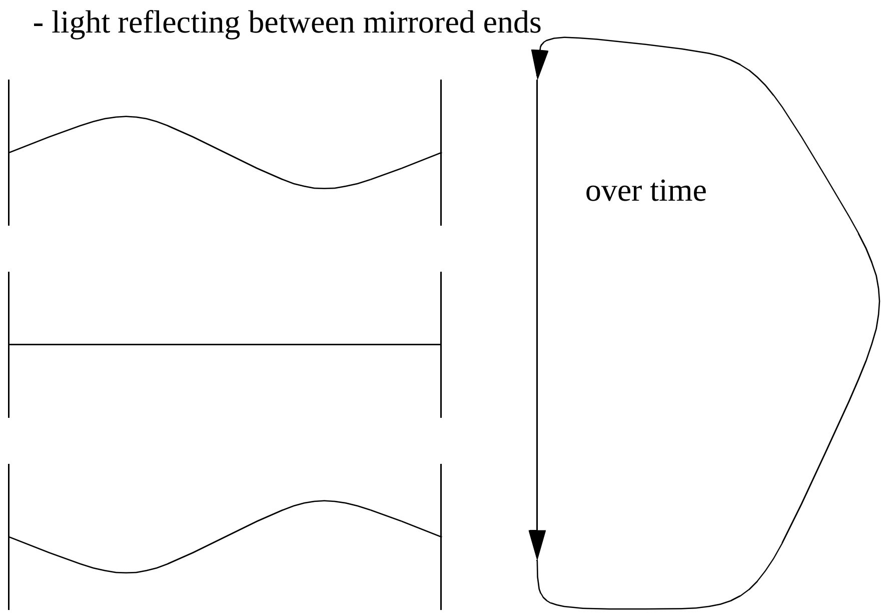
- Monochromatic - because the light is generated using specific gases, the frequency (wavelength) has a specific value. Normal white light tends to contain a wide mixture of different frequencies (a wide spectrum), but laser light is very specific.
- The light has significantly less power than a normal light bulb, but it is highly focussed, thus delivering a significantly higher light intensity.

• The principle behind lasers are
1. Excitation of light emission by electrical discharge.



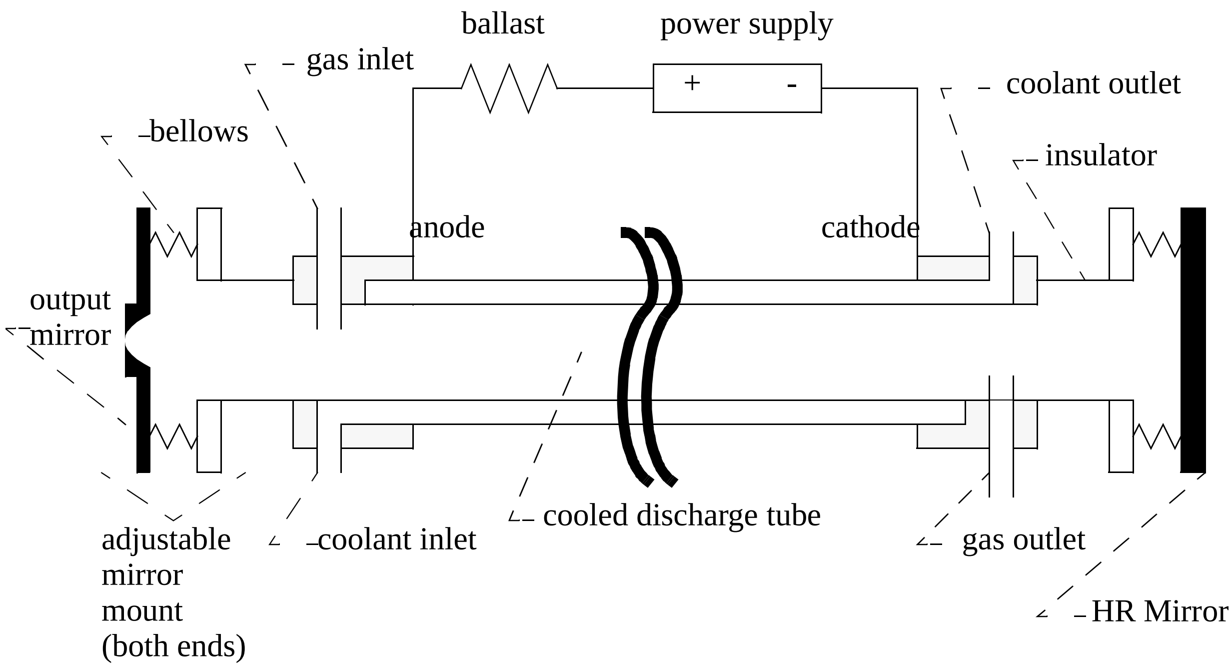
2. Resonance - the laser chamber has reflecting ends separated by a multiple of half wave-lengths one end is completely reflecting, and the other end is partially reflecting. The result is a reflection that leads to resonance.





• The height of the orbit the electron is in determines the wavelength of the photon. Larger atoms have higher orbits, therefore longer wavelengths (infrared). Smaller atoms have shorter falls, therefore shorter wavelengths (Ultraviolet).

• The electrons are caused to jump by a discharge of electrons with a potential charge in the range of KV.



AN AXIAL FLOW CO2 LASER WITH COOLING

- Various gases are used in Lasers. The contents of a laser can be a single gas, or a combination of gases.
  - e.g. in a CO_2 laser, CO_2 is used to produce light with a 10.6 micrometer wavelength. Nitrogen is used to maintain electron populations in the upper valence shell of the CO_2 molecules. Helium is used as an intracavity cooling agent.

- Lasers are very inefficient and build up excessive heat. If this heat becomes high enough it will effect the performance, and eventually damage the laser. To counteract this, heatsinks, water, and other forms of heat dissipation are used.

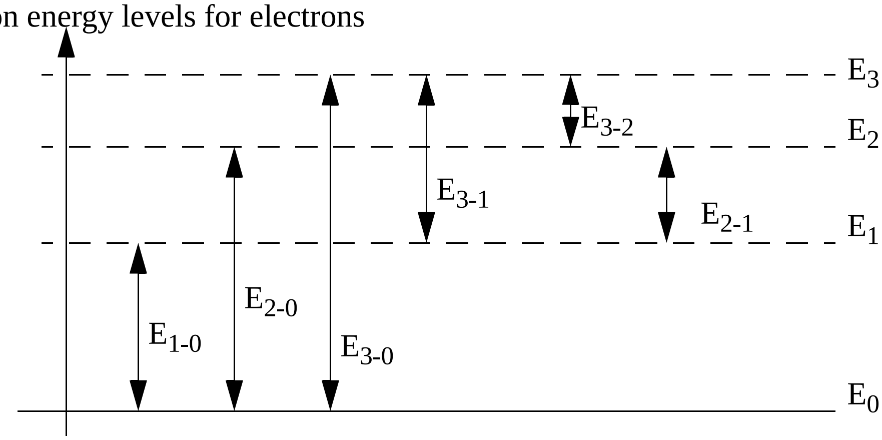
- The lasers often have sensors to shutdown when the temperatures become too high.

- 1 Angstrom A = 10^{-10}m

•

freq (Hz)	approx. wavelength (m)	classification
10^3-10^6	10^{10}	radio waves
10^6-10^8	10^7	short waves
10^8-10^{10}	10^5	microwaves
10^{10}-10^{13}	10^2	infrared (deep)
10^{14}-10^{15}	10^0	light
10^{15}-10^{17}	10^{-2}	UV and X-Rays
10^{17}-	10^{-4}	Gamma rays

transition energy levels for electrons



• Energy of a photon

$$E = hf = h\frac{c}{\lambda}$$

$$h = 6.6\times10^{-34} Js = \text{ Planks constant}$$

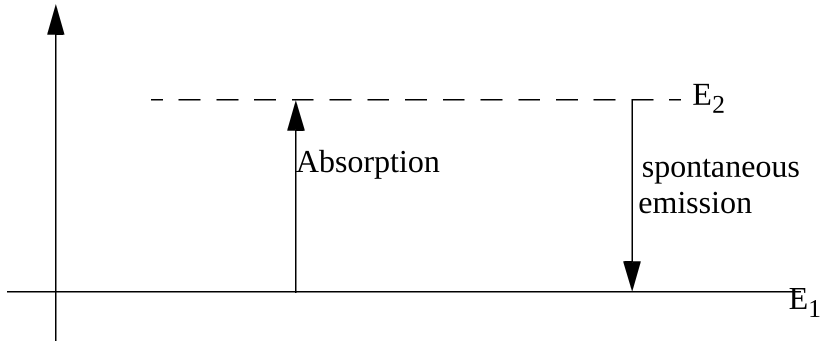
$$c = 3\times10^8\frac{m}{s} = \text{ light speed}$$

$$f = \text{ frequency of light}$$

$$\lambda = \text{ wavelength of light}$$

• Absorption is when energy causes an electron to accept enough energy to jump up one or more energy levels.

• Spontaneous emission is the drop of the electron to a lower energy orbit, and the release of the energy change as a photon.



• Absorption can be caused by energy sources, such as light, but it is also caused by the heat of an object. (as with incandescent lights)

$$W = \sigma T^4 \varepsilon$$

$$W = \text{the radiated energy (W)}$$

$$\sigma = 5.67\times 10^{-8}\frac{W}{m^2K^{-4}} = \text{Boltzmans constant}$$

$$T = \text{temperature (K)}$$

$$\varepsilon = \text{emissivity factor dependant on frequency [0, 1], table lookup}$$

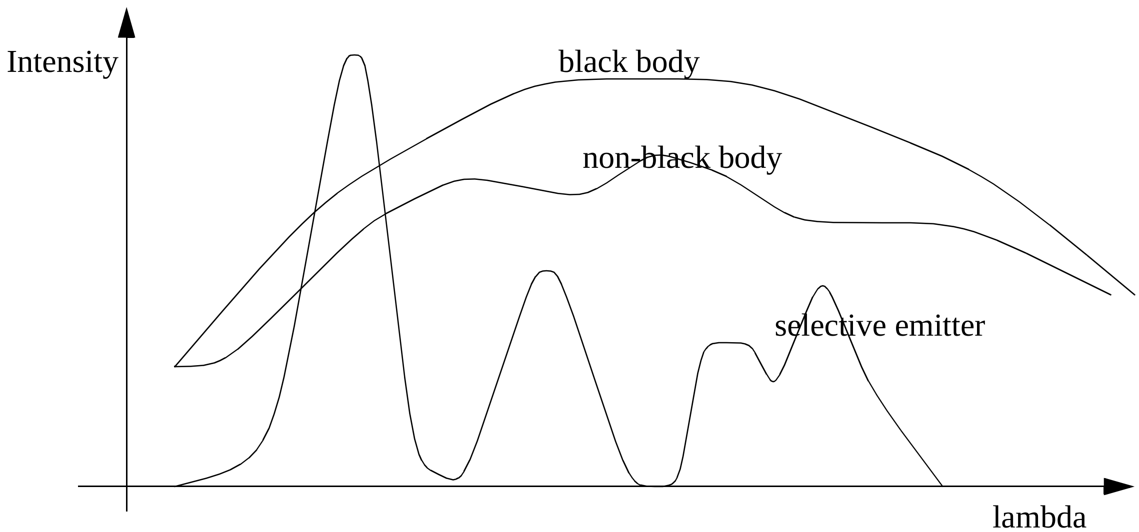
Wein’s law predicts the maximum emitted frequency.

$$\lambda_{max}T = 2.9\times 10^{-3}mK$$

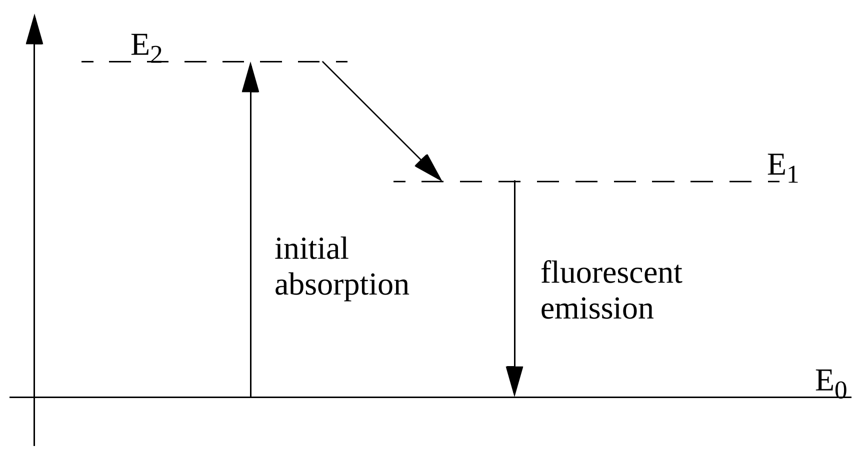
e.g. normal light sources have,

$$T_{max} = 3000C \qquad P = 6\frac{W}{mm^2}$$

• We can draw out a spectrum for frequencies emitted.



• Fluorescence is light of one color that causes emission of light of another color. (a shorter wavelength).



The state E_1 can be very stable and electron orbits might not decay for long periods of time.

• In a laser the energy levels are increased to move more than 50% of the electrons (in the lasing material) to a higher energy state.

• The usual population inversion allows incoming photons to cause a new photon to be emitted without being absorbed itself. The two photons have,

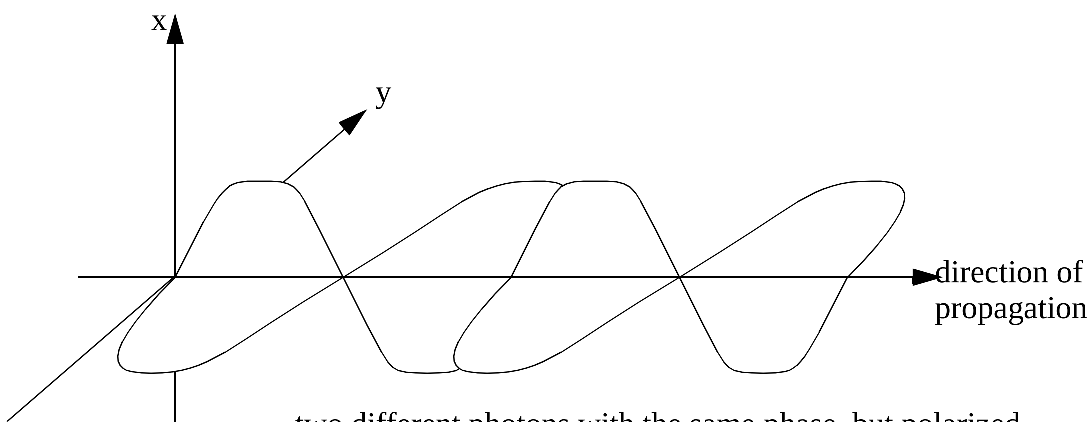
- the same frequency
- the same phase
- the same direction

**** This effect is also a 2 times amplification

• How a laser works,

1. The electrical/light discharges are used to cause electron population inversion and cause a few spontaneous emissions of photons.
2. The new photons travel in all directions, but some travel toward the mirrors, where they are reflected back and forth between the mirrors.
3. As the photons travel, they cause the generation of other photons travelling in the same direction.
4. This builds until the laser has a high intensity output.
5. The output beam escapes through one end of the laser that has a half silvered mirror.

• Laser light is polarized



two different photons with the same phase, but polarized 90 degree to one another

• Various lasers are suited to different applications.

Application	monochromatic	low divergence	single or low order mode	coherence	high output power	efficiency	Laser normally used
Precision measurement of length	X		X	X			He-Ne
surveying and alignment	X	X					He-Ne
rangefinding		X			X		Nd:YAG, GaAs
drilling	X	X			X	X	Ruby, Nd:YAG
cutting	X	X			X	X	CO_2
welding	X	X			X	X	CO_2, ruby, Nd:YAG
opthamology	X	X					Ruby, argon ion
pollution detection	X						Dye, GaAs
holography	X		X	X			Ruby, Nd:YAG, Argon ion, He-Ne
communications	X	X		X			He-Ne, GaAs

• Efficiency of lasers is often about 0.1% for gas, but CO_2 can be as high as 18%.

64.1.1 References

Harry, J. E., Industrial Lasers and Their Applications, McGraw-Hill, London, 1974.

Hugel, H., Lasers in Manufacturing, Proceedings of the 5th, International Conference, Sept., 1988, Stuttgart, West Germany.

Ready, J. F., Lasers in Modern Industry, Society of Manufacturing Engineers, Dearborn Michigan, 1979.

Soares, O. D. D., and Perez-Amor, M., Applied Laser Tooling, Martinus Nijhoff Publishers, Lancaster UK, 1987.

64.2 LASER CUTTING

• Good for,

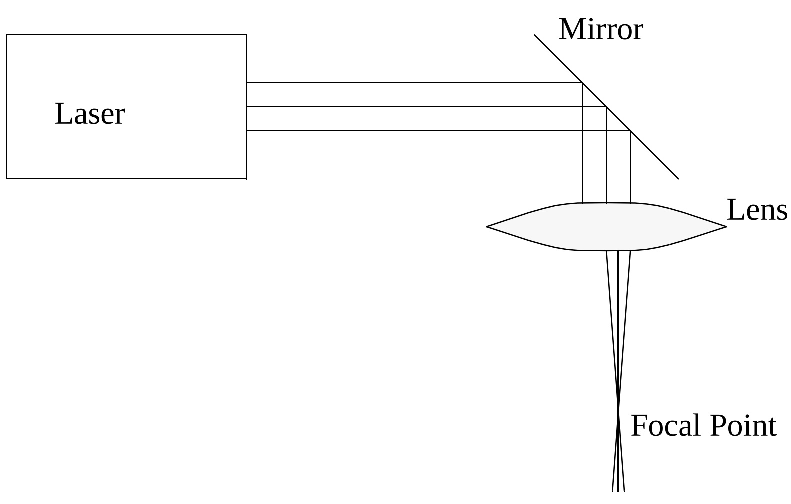
- thin work pieces that would be greatly effected by contact force (e.g. soft or brittle)
- parts that are too complex for saws and other cutters
- materials normally too hard to machine with traditional methods. The laser effects the thermal, not hardness cutting conditions.

• Used for,
  - cutting
  - welding
  - scribing
  - drilling
  - heat treating

• Results,
  -less part deformation
  - reduced part grinding and deburring
  - lighter fixtures

• Can be used for 2D or 3D workspace.

• The cutters typically have a laser mounted, and the beam is directed to the end of the arm using mirrors.



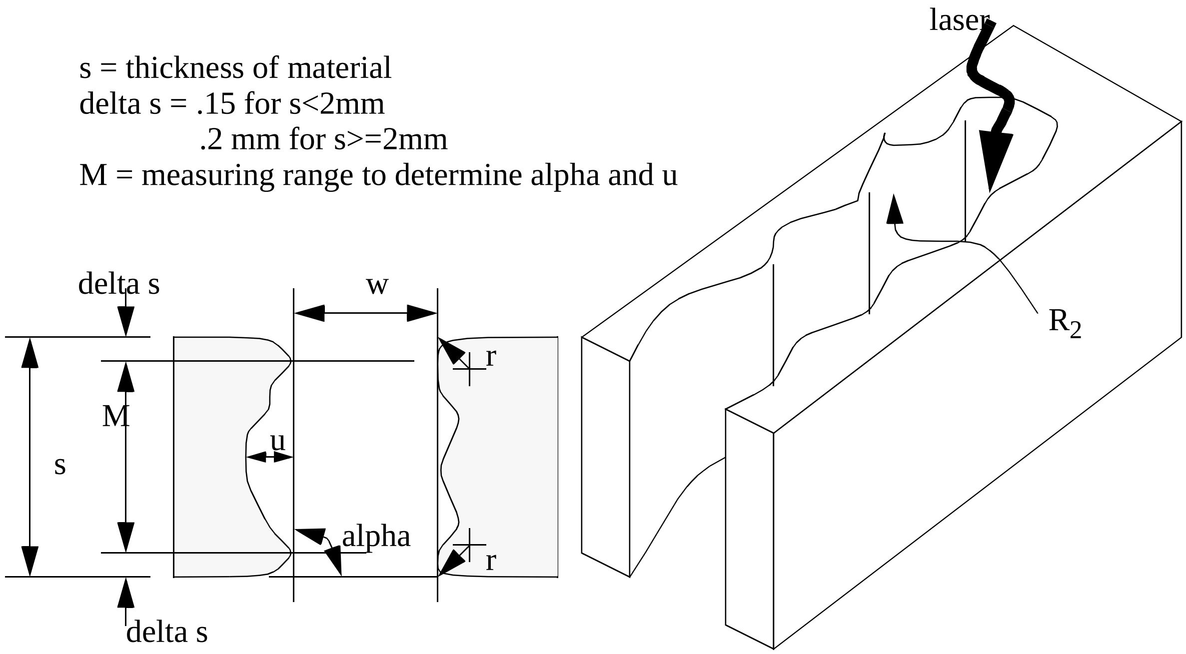
• Mirrors are often cooled (water is common) because of high laser powers.

• The light focuses on the surface, and vaporizes it. The basic process is,
  1. Unheated material.
  2. Heating begins and metal becomes reflective.

3. Heating continues and reflectivity decreases.
4. A molten zone is established.
5. Material vaporizes, consuming most of the laser energy. Very little energy goes into heating the surrounding material.
6. Outgoing vapor is struck by the laser and further energizes, producing plasma.

• The cuts look like,

s = thickness of material
delta s = .15 for s<2mm
.2 mm for s>=2mm
M = measuring range to determine alpha and u



R_2 = surface roughness
u = rectangular and inclination tolerances
alpha = flank angle
r = radius of cutting edge (upper/lower side)
w = kerf width (upper/lower/middle as measured by M)

• Dross is metal that has been collected on the underside of the sheet and protrudes as a burr would.

• Laser cutting is often assisted with a gas,
- oxygen is used to help when cutting metals. This happens because the oxygen initiates the exothermic reactions to increase cutting rates, and it cools surrounding material. The user must be aware that the oxygen reacts with the heated metals and forms an oxide layer on the cutting edge.

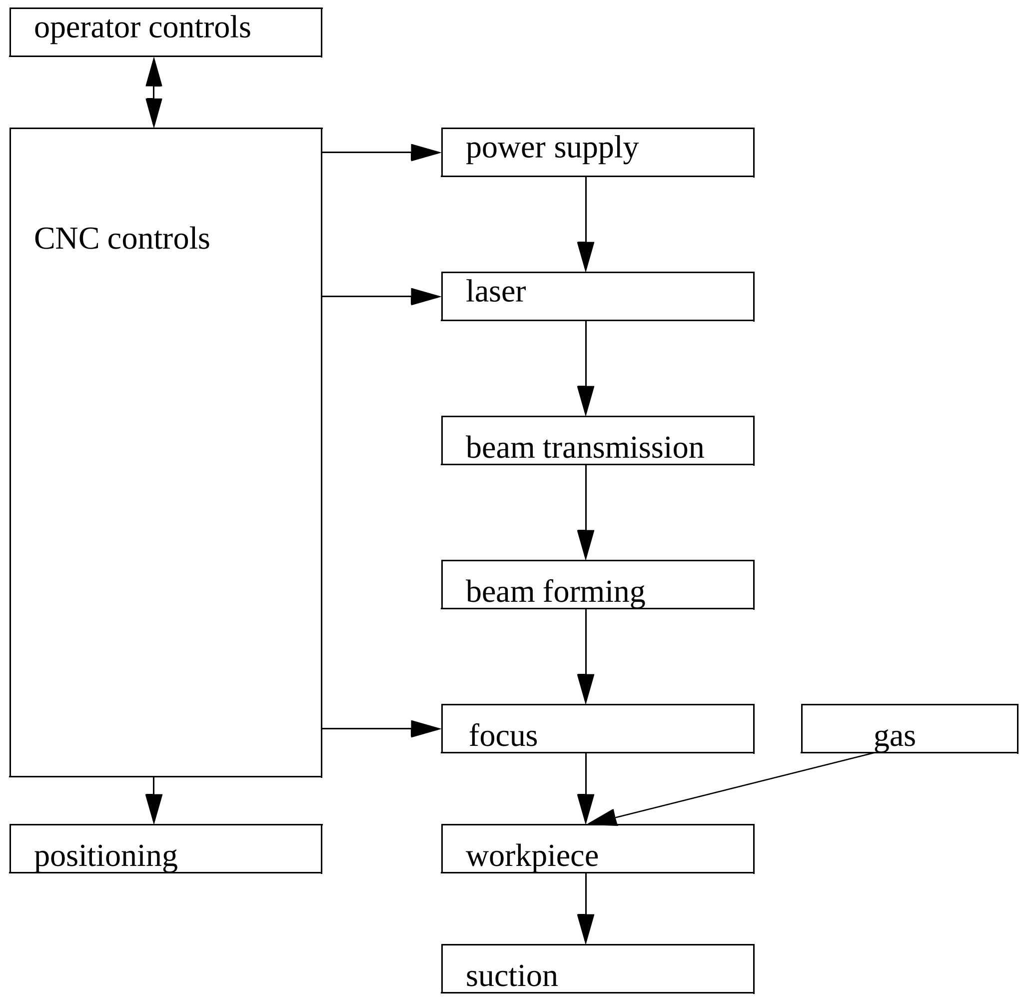
• Gas flow tends to “blow” vaporized metal away from the cutting zone, and minimize the beam absorption in the vapor.

• Slag-collectors and vacuums are used to clear debris and vapors in these systems.

• Cutting speeds are related to material thickness, and laser power.

• Typical laser components are,
  - laser tube/laser power supply/controls
  - mirrors to direct laser to end of tool
  - focusing optics
  - nozzle with optics, gas delivery, etc.
  - workpiece fixture
  - nozzle/fixture positioner
  - fume extractors for vapors
  - slag collectors
  - enclosure
  - safety interlock system

• Additional laser cutter components are,
  - CNC machine/robot
  - diagnostic software/sensors for beam condition
  - beam splitter for multiple operations.



• The major design decisions are,
  a) Move the workpiece and maintain fixed optics.
  b) Move the “flying optics” and keep the workpiece steady. Large parts are easier to deal with when they don’t move, but the changes in the optics system can cause focussing problems.

• Laser speed example
  - 5KW laser, 5mm thick carbon steel cut at 1m/min.

$$W_L = 5KW$$

$$R_L = 1000\left(\frac{W}{\left(\frac{mm^3}{min}\right)}\right)$$

$$V = (0.01m)(5m)(0.01m) = 0.0005m^3$$

$$Q = \frac{W_L}{R_L} = \frac{5KW}{1000\left(\frac{W}{\left(\frac{mm^3}{min}\right)}\right)} = 5 \times 10^{-9}\left(\frac{m^3}{min}\right)$$

$$t = \frac{V}{Q} = \frac{0.0005m^3}{5 \times 10^{-9}\left(\frac{m^3}{min}\right)} = 10^{-5}min$$

• Some commercial specifications for the Trumpf L5000 are given below,

Positioning	Work Volume	118 by 78 by 29.5 in.
	Single Pallet Size	59 by 78 in.
	Double Pallet Size	118 b 78 in.
	X Axis Travel	126 in.
	Y Axis Travel	78 in.
	Z Axis Travel	29.5 in.
	B Axis Orientation	±120°
	C Axis Orientation	n(360°) continuous rotation
	Range of Auto Focus	± 0.200 in.
	Traverse Speed	1200 in./min., 180°/sec.
	Resolution	±0.001 in., ±0.01°
	Accuracy	±0.004 in.
	Repeatability	±0.002 in.
Machine Size	Width	284 in.
	Depth	472 in.
	Height	158 in.
	Table Height	28 in.
	Weight	33,000 lbs.
Laser	Laser Type	CO2 Gas
	Performance	750W continuous wave
	Adjustment Range	40-750 W continuous wave
	Beam Mode	TEMoo
	Pulse Frequency	100Hz - 10 KHz
	CO2 Consumption	0.06 ft3/hr.
	He Consumption	0.56 ft3/hr.
	N2 Consumption	0.25 ft3/hr.
	O2 Consumption	53-106 ft3/hr.
Services	Electrical Supply	460V, 60 Hz, 39 KVA
	Pneumatic Supply	0.75 ft3/hr.

• Summary of Laser machining;
- mechanics of material removal - melting, vaporization
- medium - normal atmosphere
- tool - high power laser
- maximum mrr = 5 mm^3/min
- specific power consumption 1000W/mm^3/min
- critical parameters - beam power intensity, beam diameter, melting temperature
- material application - all materials

- shape application - drilling fine holes
- limitations - very large power consumption, cannot cut materials with high heat conductivity and high reflectivity.

64.2.1 References

Ghosh, A., Manufacturing Science, Ellis Horwood Ltd., Chichester, UK, 1986.

Weiss, N., “Laser Cutting?”, A Project report submitted for MEC732 in the fall of 1993.

64.3 PRACTICE PROBLEMS

1. If the frequency of light from a laser was to be halved, what physical changes would have to be made to the laser?

2. Describe the basic process of laser cutting.

3. What is the major limiting factors for depth of cuts using lasers?

ans. The diffusion of the beam, and distortion due to gases limit laser depth to a reasonable range of about one inch.

4. We are to make a cut, that is 1/4in thick and 10in long, using a laser. If the laser kerf (cutting slot) is 1/16in wide, what is the cutting time?

5.

65. RAPID PROTOTYPING

• The key concept is RAPID - generally this is an all-in-one-step production of a part geometry.

• Parts are used for,
  - prototypes to allow fast review of part shape, simple assembly, aesthetics, manufacturability, etc.
  - low volume production - very small numbers of parts can be made using this technology.

• General advantages,
  - reduce prototype/production times from months to weeks or days
  - a physical model is easier to "sell" to customers and management
  - physical models are easier to check for errors. Graphical methods often result in cluttered views
  - avoids the high cost of prototype tooling, and allows (more) design iterations
  - prototypes costs can be lower than production types

• General disadvantages,
  - very expensive capital costs
  - tolerances are generally >.005"
  - primary materials are specialized, and other steps are required to produce metal parts

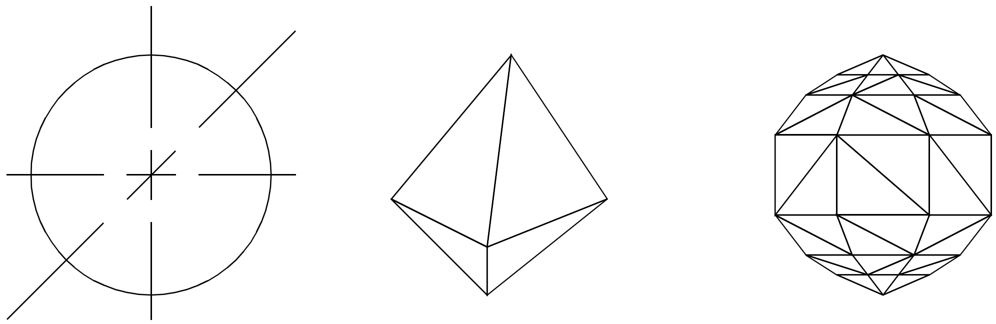
65.1 STL FILE FORMAT

• Originally developed for use with stereolithography, but now used by many other processes.

• The standard for Rapid prototyping systems

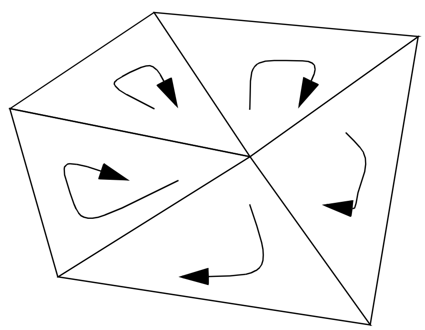
• Basically connected 3D triangles

• 3D smooth surfaces are tessellated into triangles. the higher the degree of tessellation the closer the surface approximates the smooth surface.

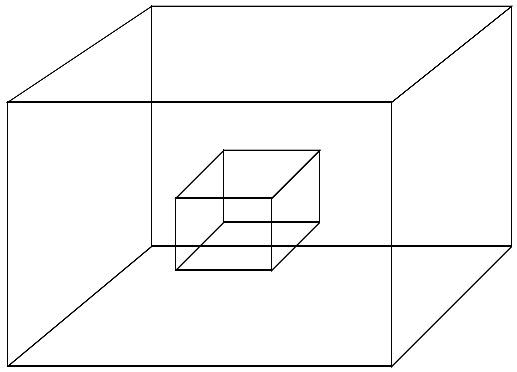


sphere coarse tessellation fine tessellation

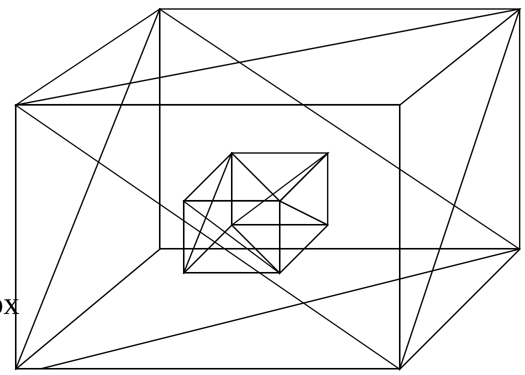
• The triangles are defined
1. with a direction of nodes defined clockwise for the out direction
2. with similar nodes at the corners of triangles. If the triangles don’t overlap, the model will have gaps and be invalid.



• A general approach to determining a rapid prototype slice is to use a ray projection through the collection of polygons. When the ray strikes a triangle it is in/out of the solid. (This is a simple geometrical problem.) A set of lines constitute a slice.

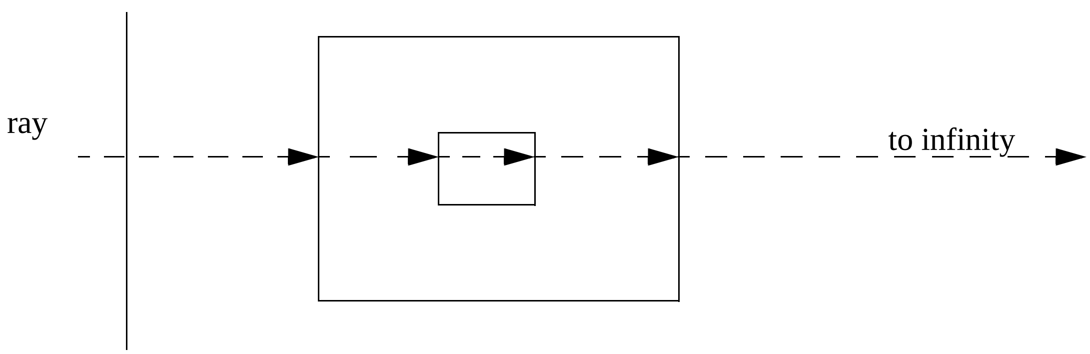


a hollow box

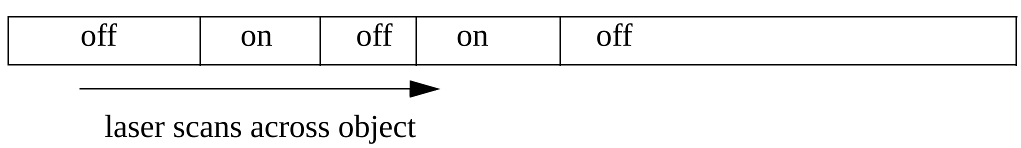


an STL tessellated box

3. Fire a “ray” through the triangles, and find intersections

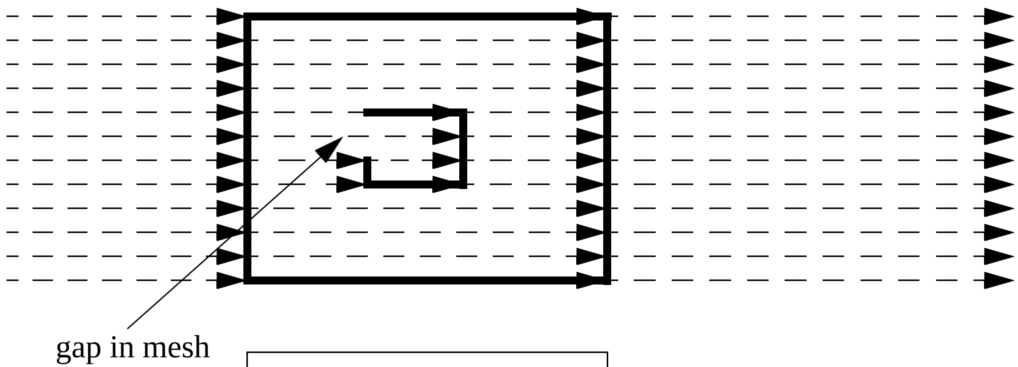


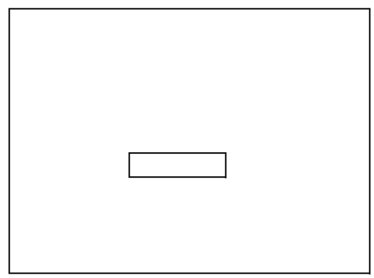
For the stereolithography machine we need to develop a “scan line” for the laser. When the laser scan-line (the ray) is “in” the part, the laser is on, and thus developing the light hardening polymer.



- If polygon vertices don’t match up, then there will be gaps between the polygons. This can result in non contact, that leads to material added/subtracted unexpectedly.

e.g., the result of a gap in triangle meshes

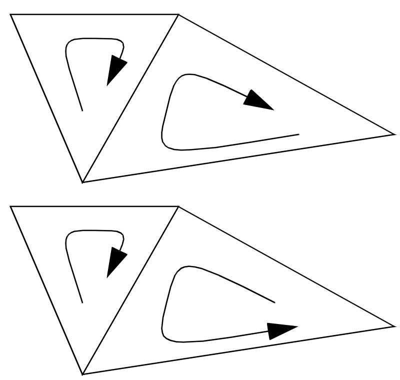




The part produced has a problem with the hole, caused because the test ray passed through a gap in the triangle mesh.

• Another problem can arise from mobius strip representations. Because the outside is defined by the order of node definitions, a mobius strip will lead to a back touching a front.

Picture of mobius strip



3D systems produces a software package to verify STL geometries

65.2 STEREOLITHOGRAPHY

• Invented by Charles Hull 1984

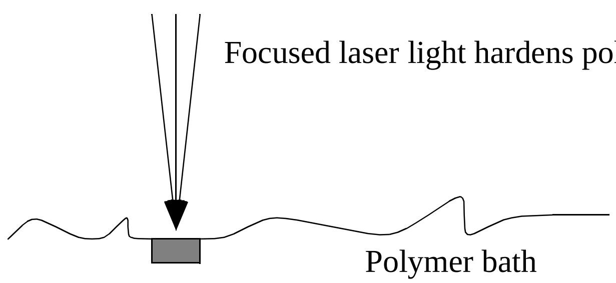
• Now developed by 3D systems Inc (90% of market in 1991)

• Units available since 1988

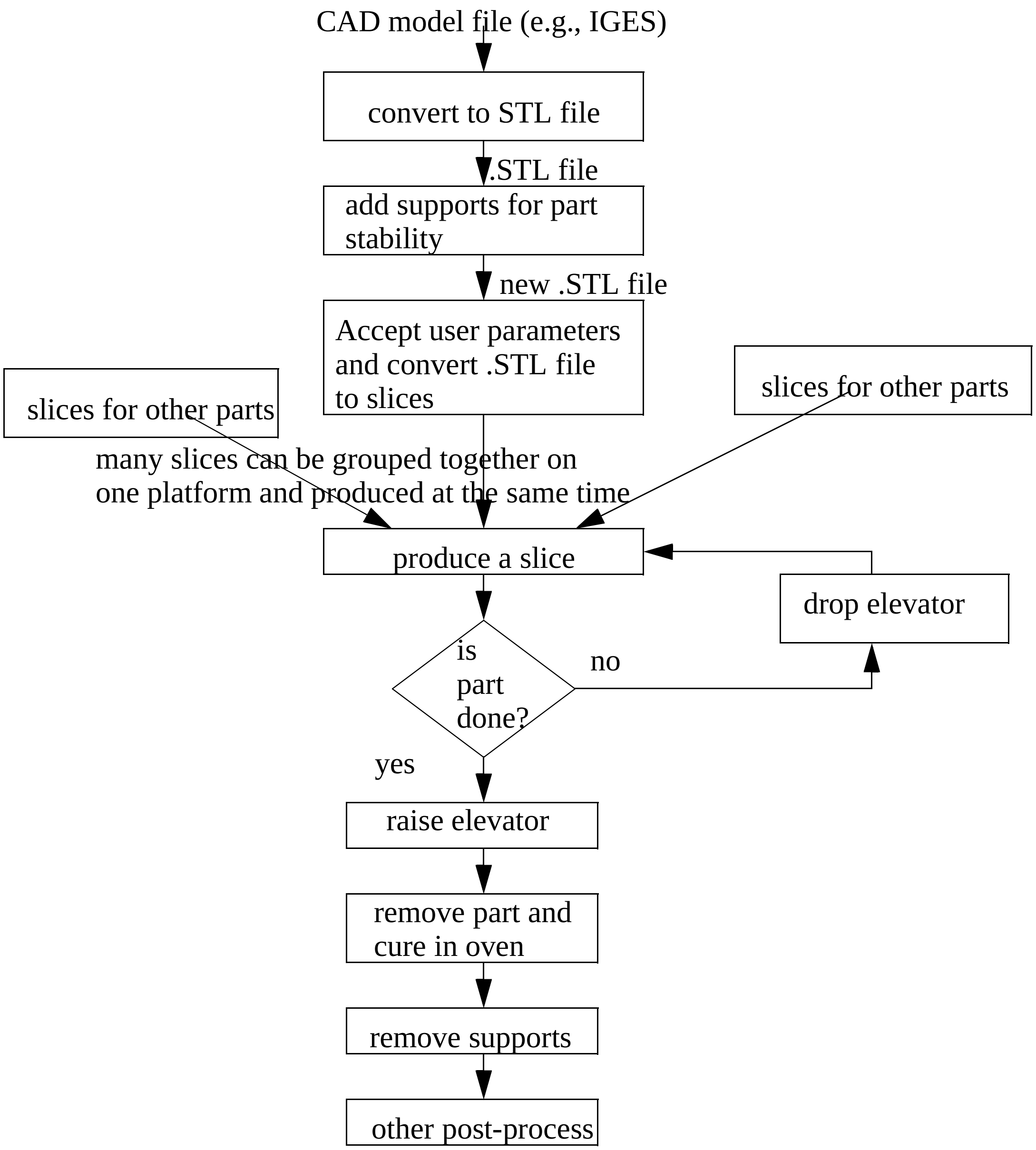
• Other similar machines,

Product Name	Maker	Location
JSC	Sony	Tokyo, Japan
SOUP	CMET	Tokyo, Japan
SOMOS (DuPont)	Teijin Seiki	Tokyo, Japan
Colamm	Mitsui	Tokyo, Japan
Stereos	EOS	Munich, Germany
SLA190/SLA250/SLA400/SLA500	3D systems	California, USA

• The physics of the process is based on a photo-sensitive polymer that will harden when exposed to high intensity laser light



• The process uses a vat of photopolymer with an elevator for the part to lower on. The elevator starts at the top of the bath, and drops down a layer at a time as the laser develops each layer.



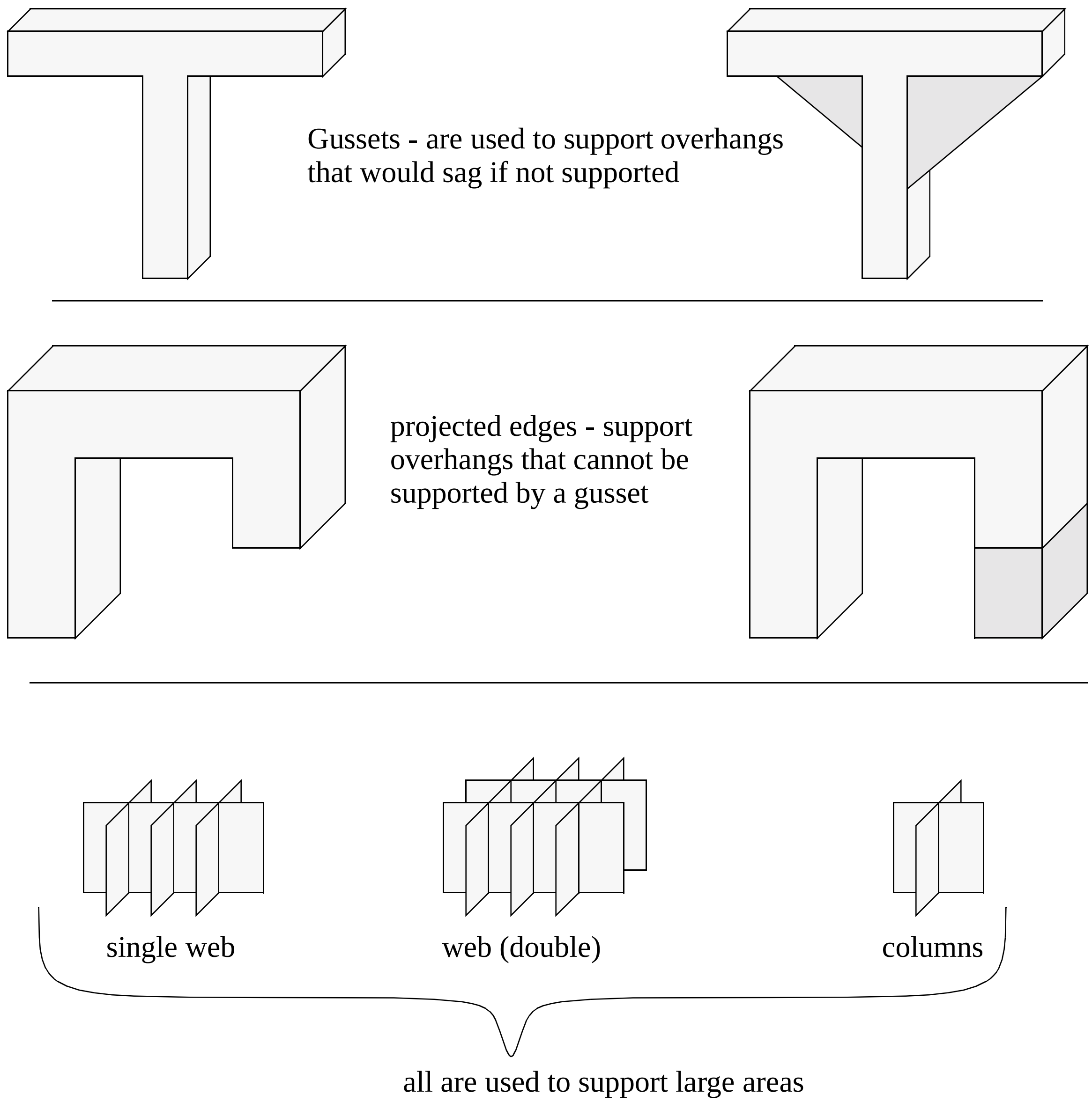
65.2.1 Supports

• supports can be created in the CAD model of afterwards with programs such as bridgeworks (by Solid Concepts, Los Angeles, California)

• The uses of supports are,
  - to stabilize overhangs
  - to prevent the recoating blade from striking the elevator platform
  - to correct for variations in elevator platform surface.

- to allow easy removal of the part from the platform
- unattached parts

• There are a few basic supports used,



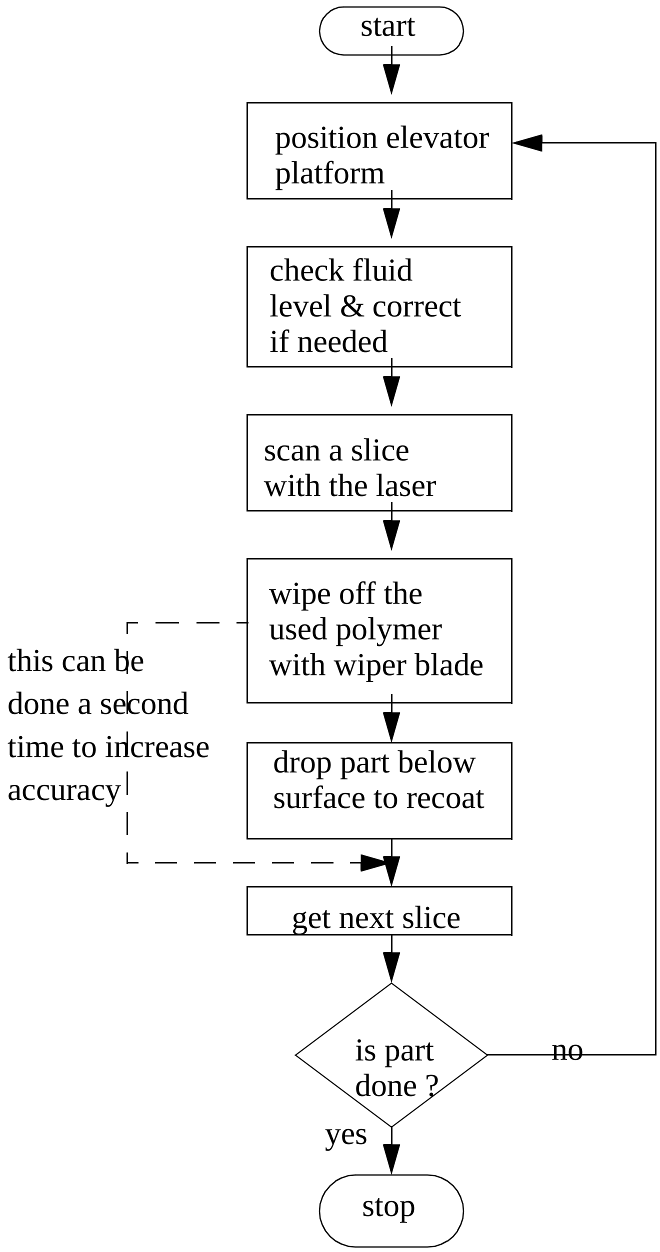
65.2.2 Processing

• CAD files are converted to .STL files

• .STL files converted to slices using the parameters, such as,
- various parts on a platform (different .STL files can be mixed)
- blade sweeps per layer and sweep period, and “z-wait” to wait after recoating for mate-

rial mixing

• The SL process



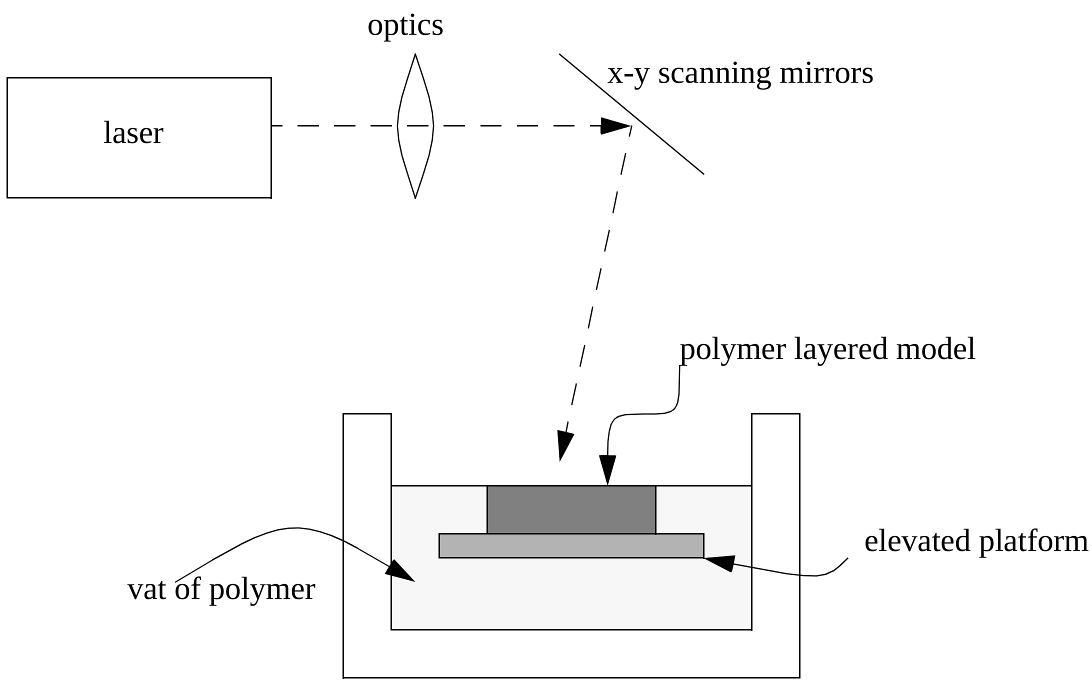
• The part is then immersed (approx. 0.5”) with a waiting period to recoat the surface and the wiper blade is used to clear the excess fluid from the top of the surface. (Note: the sweep is optional, but it is used to get consistent thickness)

• The part is then moved, and the laser has a focal point near the surface that hardens the polymer.

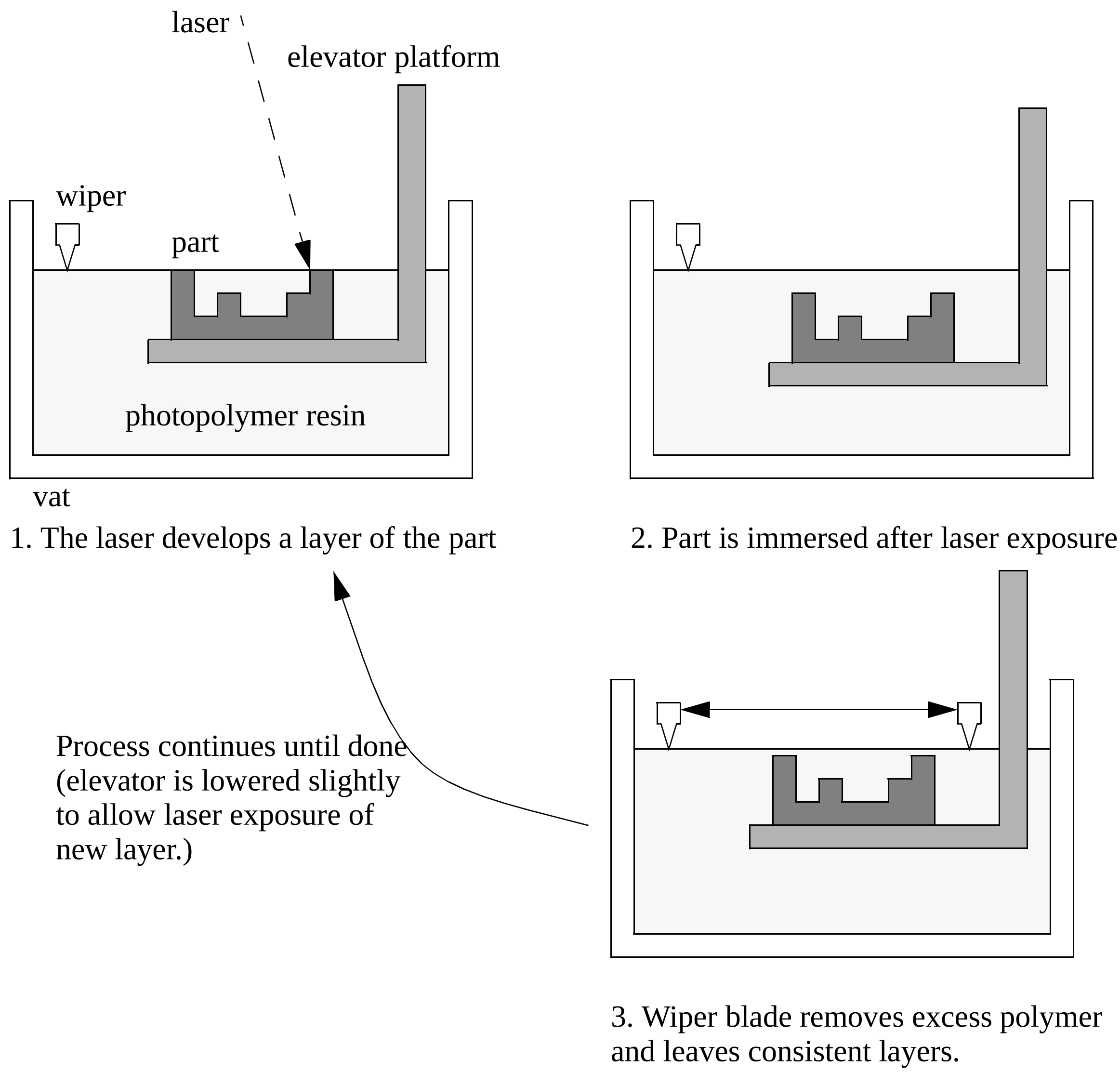
• As the polymer hardens, it shrinks. This shrinkage causes a change in the volume of the fluid. To correct for this the tank has a fluid level detector that will control an adjustable reservoir that will add enough fluid to compensate for volume change.

• Layers vary in thickness from 0.002” to 0.020”. This is controlled by the amount the platform is lowered into the photopolymer. Thinner layers give smoother, higher tolerance parts (with polymer more cured) but these take longer.

• The laser is stationary, but optics and mirrors are used to guide the beam to x-y coordinates on the surface of the fluid.



• The Slice Cycle

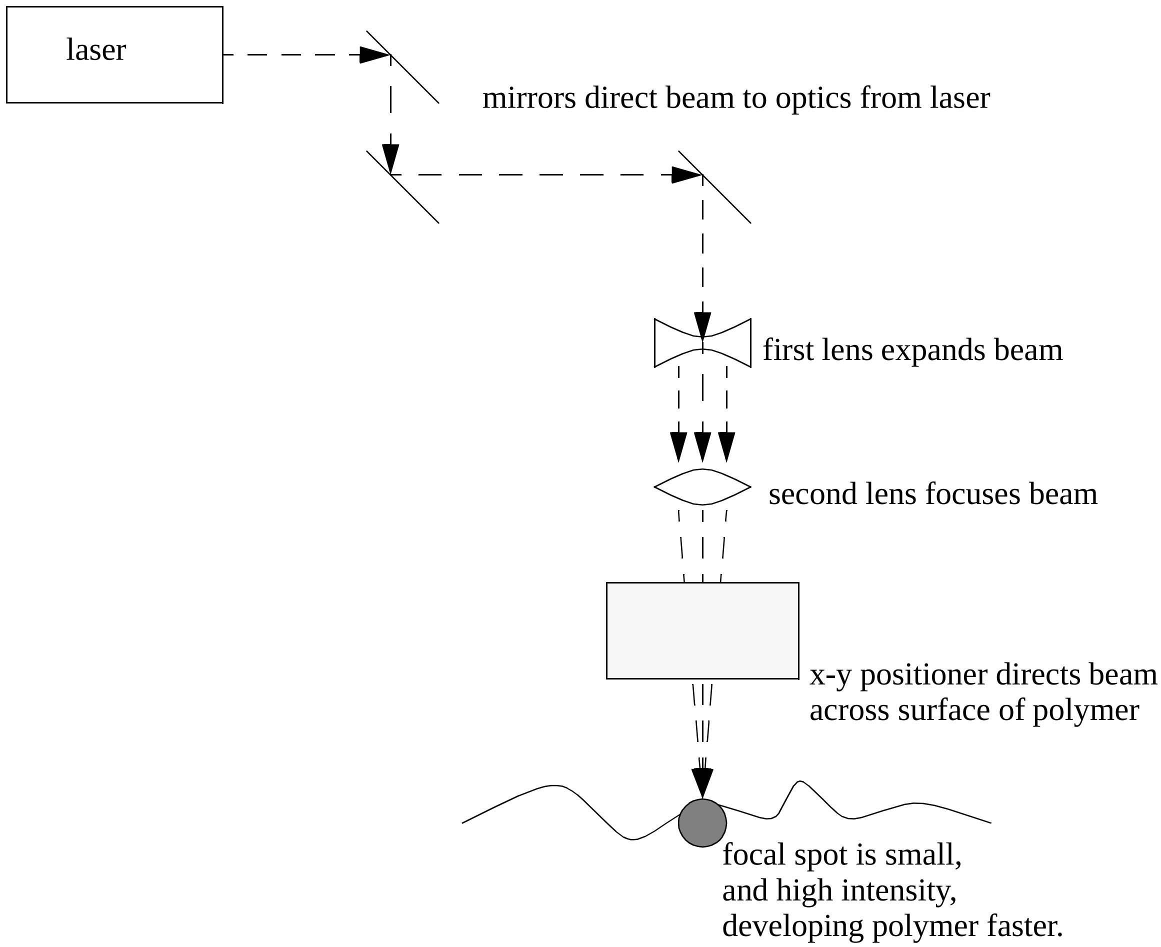


• After the part is done, the part raises above the fluid, and resin drains out. The elevator can be tipped to drain trapped volumes.

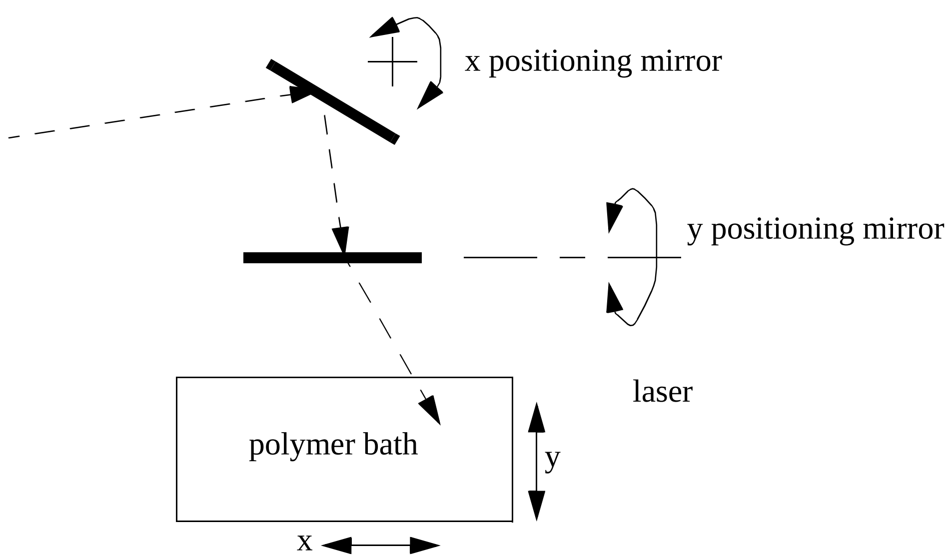
• After removal from the bath the part is cleaned off with towels and Q-tips, and hardening of the resin is completed in a curing oven.

• The laser - is often about 10-200 mW (more power is required for faster operation)
  - often He-Cd or Argon-Ion to produce UV radiation about a 320-370 nm wavelength

• The optics - the user can set the focal distance of the laser to the range of the slice thickness.



• x-y positioning - uses 2 computer controlled mirrors to reflect beam.



• polymer vat - generally holds 20-200 liters of resin. Can be interchanged to speed up change of resin (lower downtime).

• The photopolymer is light sensitive and toxic. Therefore the operation vat is often out of sight and the unit uses a ventilation unit to evacuate fumes.

• Post Curing Apparatus (PCA) - uses high power ultraviolet light to complete the curing of mostly solidified polymer.
  - times are typically 1 hour and up
  - after curing parts become non-toxic

• Advantages,
  - can run without supervision
  - high detail and accuracy
  - sharp-edges tend to get “filled” by resin, thus reducing the “stepped” effect between slices
  - popularity makes this process well supported

• Disadvantages,
  - extra time required for postcuring (up to 16 hrs)
  - polymer shrinks as it hardens - the result is stress that warps the part
  - toxic chemicals (resin and cleaners)
  - limited selection of chemicals (general cost $100-200 a liter)
  - experts needed for process setup
  - addition of supports needed
  - work required after to remove supports

• Weave techniques
  - used to reduce curing time and part stresses that cause warping
  - most of the part is cured before, because of multiple exposures
  - staggered hatching uses exposure in-between lines of previous exposure

• SL units from 3D systems (also see attached specs)

UNIT	work volume	Cost	Comments
SLA190	7.48” by 7.48” by 9.84”	$105,000(US)	
SLA250	10” by 10” by 10”	$145,000(US)	
SLA5000	20” by 20” by 23”	$???,000(US)	
SLA3500	13.8” by 13.8” by 15.7”	$???,000(US)	
Actua	10”by8”by8”	$65,000(US)	
SLA 350		$380,000(US)	

• Units are sensitive to vibration

• Application
    - basic polymer is slightly brittle and therefore is best suited to conceptual models
    - “Exactomer” is well suited to trial assemblies, and has been used to make secondary rubber, and spray metal tooling (being less brittle it won’t break when being removed from molds).
    - Investment casting molds can be made using hollow cores (that minimize polymer expansion when melting) that won’t crack the mold.
    - Dupont is creating an investment casting resin that won’t crack the mold.

• In some research fibers have been added to a stereolithography process to obtain higher strengths. [Hyer, 1991]

• An inexpensive stereolithography unit can be made using UV light guided by a fiber optic cable.

• Large parts can be created in pieces and glued together. For example, an impeller can be created in sections. The sections are glued with normal resin, and hardened with a UV lamp. Metal inserts can be added by press fitting, and the part can be machined for precision. This process might cost 1/3 of normal prototype costs.

• There are a wide variety of techniques for creating cast metal parts and molds from STL resin parts [Ashly, 1994]. These include parts cast from SLA tooling directly. For example, SLA wax parts can be used to do investment casting.

65.2.3 References

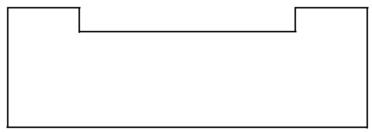
Hyer, M.W., and Charette, R.F., “Use of Curvilinear Fiber Format in Composite Structure Design”, AIAA Journal, 1991, pg. 1011-15.

65.3 BONDED POWDERS

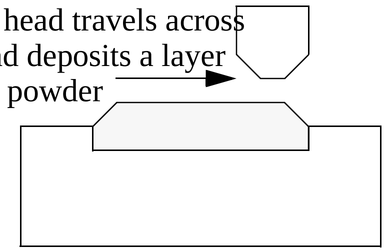
• Basically a loose powder is spread in a layer, and an bonding adhesive is selectively applied to harden a slice. Layers are continually added until one or more parts are completed.

• A trademarked name for this process is 3DP (3 Dimensional Printing)

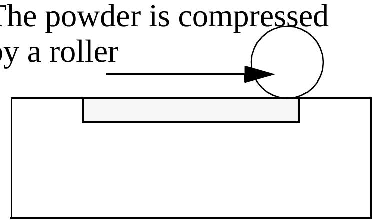
• The general sequence is pictured below, An elevator drops and the space for a new layer is created



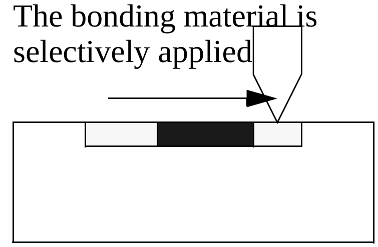
A head travels across and deposits a layer of powder

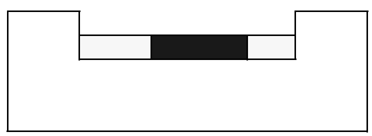


The powder is compressed by a roller



The bonding material is selectively applied





The layer drops down, and a new layer of powder is added. This creates until all of the needed layers have been created.

• The powders used by this process are starch based/cellulose powders.

• Parts can be colored using dyes

• The water based bonding adhesive is ???unknown???.

• The unbonded powder acts to support the part, and eliminates the need for other supports. This also allows multiple parts in a single build.

• After the part is complete the loose powder is removed. Powder can be easily removed from hollow and recessed cavities.

• Because the part is made of a bonded powder, the final part is porous. Higher part density can be obtained by impregnating parts with materials such as wax or epoxy. Parts may also be sanded for better surface finish.

• As expected there will be some dimensional shrinkage, this will be less than 1% for height and less than 1/2% on the build planes.

• A machine (Z402) is produced by Z-corporation, and the details are given below,

Build speed approx. 1.85 in/hr height for a 4” by 8” area
Maximum build volume 8” by 10” by 8”

Layer thickness 0.005” to 0.009”
Printing head is 0.36” wide and has 128 jets
Equipment size 29” by 36” by 42”
Mass 300 lb.
Consumable materials approx $0.65 per cubic inch of finished part
No special environmental requirements
Basic unit costs $59,000
An IBM compatible PC is required to run the machine

• Advantages,
  - inexpensive
  - fast
  - complex geometries
  - suitable for desktop usage
  - investment casting can be done from models
  - colored parts

• Disadvantages,
  - part material limited and not engineering materials
  - lower part strength

65.4 SELECTIVE LASER SINTERING (SLS)

• Powdered material is fused together in layers using a laser

• The powders need fine grains and thermo-plastic properties so that it becomes viscous, flows, then solidifies quickly.
  - nylon
  - glass filled nylon
  - somos (elastomer)
  - polycarbonate
  - trueform (ceramic??)
  - sandform ??
  - rapid steel (metal)
  - copper polyamide (metal)

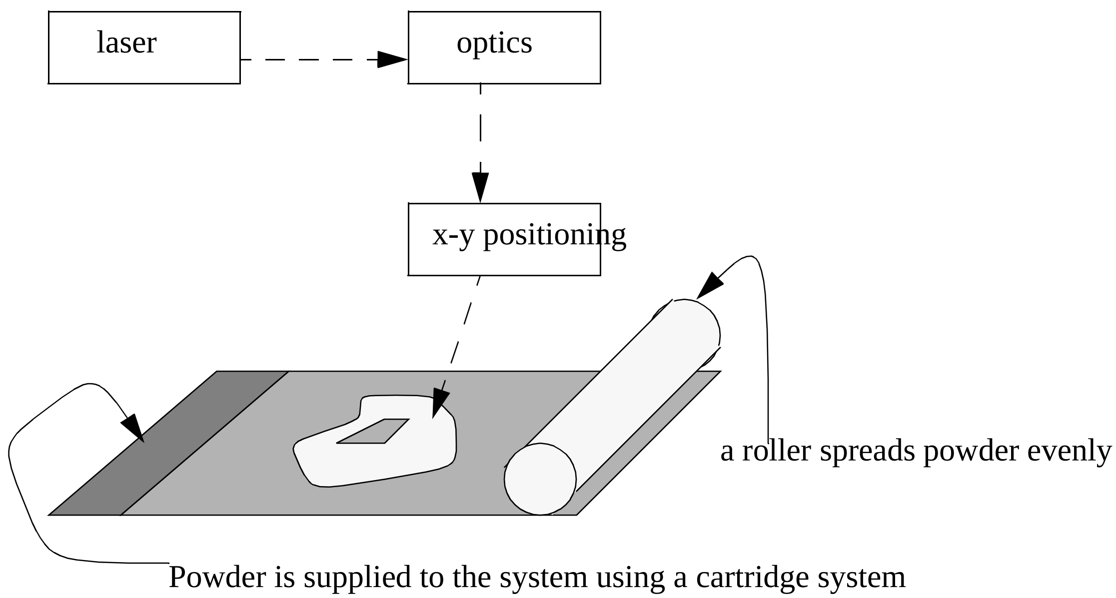
• invented in 1986 by Carl Deckard

• marketed by DTM corp. (Sinterstation 2000)

• The process uses a heated chamber (near the powder melting temperature)

• The product is split into slices from the .STL file and created one layer at a time by spreading layers of powder, sintering the powder with a CO2 laser, then adding new layers of powder and sintering until done.

• When done the part is inside a cake of powder, and putty knives and spatulas are used to remove the loose powder



• Supports not needed as the unsintered powder supports overhangs/etc.

• powder can be reused

• slow cooling of the parts can prevent distortion due to internal stresses.

• The laser is about 50W infrared (about 10000nm) This power level is much higher than stereolithography

• Optics and x-y scanner are similar to SL

• the process chamber runs hot to decrease the power required from the laser, and reduce thermal shrinkage that would be caused by a difference in operation and cooling temperatures.

• The hot chamber is filled with nitrogen (98% approx.) to reduce oxidation of the powder.

• rate of production is about 0.5-1” per hour

• Advantages,
  - inexpensive materials
  - safe materials
  - wide varieties of materials: wax for investment casting; polymers/nylon for assembly prototypes

- supports not needed
- reduced distortion from stresses
- produce parts simultaneously

• Disadvantages,
- rough surface finish (“stair step effect”)
- porosity of parts
- the first layers may require a base anchor to reduce thermal effects (e.g. curl)
- part density may vary
- material changes require cleaning of machine

• DTM markets the Sinterstation 2000 for $250,000(US) to $497,000(US) depending upon the selection of 1, 2, or 3 materials (investment casting wax, nylon, or polycarbonate). The Sinterstation 2500 starts at $400,000

• Development is being done on,
- new materials
- high power lasers for metal powders/etc.

• Selected specifications for a Sinterstation 2000 are given below,

Parameter	Details
Input File Format	STL
Work Volume	12” dia. by 15” height
Slice Thickness	0.003” to 0.020”
Laser	50W CO_2, class 1, highly reliable/stable, 10,000 life, rechargeable
Laser Gas	99% dry Ni at 50 p.s.i.
Process Chamber Gas	Ni at flow rate of 1.5 scfm or peak 5 cfm
Components Weight and Size	Sinterstation 2000, 4500 lbs, 155” by 59” by 75”
	Process chamber/powder engine, 3000 lbs, 81” by 38” by 75”
	Controls Cabinet, 750 lbs, 33” by 59” by 75”
	Atmospheric Control Unit (chamber heating), 750 lbs, 57.5” by 20” by 73”
	Rough Breakout Table (for post processing), 150 lbs, 45” by 29” by 48”
	Rough Breakout Air Handler, 350 lbs, 25” by 31” by 52”
Power Supply	208/240VAC, 70A, 60Hz AND 120VAC, 20A
Network	Thin wire, thick wire or twisted pair ethernet
Modem	19.2Kbaud
Environmental	Designed for operator safety, oxygen monitor needed because of Ni use. Non-toxic materials

65.5 SOLID GROUND CURING (SGC)

• Basic Process,
1. A computer program preprocesses a part so that it is in sliced layers.
2. A plate (glass?) is charged selectively and coated with a back powder. This process is much like photocopying.The result is a photographic mask of clear and opaque areas for a single slice of the part.
3. A thin layer of photopolymer is spread in a part vat.
4. The mask is placed over the photopolymer and a UV lamp is used to expose the layer and selectively harden the polymer.
5. The photographic plate with the mask is cleaned.
6. The unhardened polymer is removed from the surface.
7. A find layer of wax is deposited and hardened.
8. The surface is milled flat for uniform thickness.
9. The process begins again at step 2 and continues until all of the layers have been added. Note: Some steps can be done concurrently for the mask and the vat (i.e., 2,5 AND 3,6,7,8) to decrease build times.

• Developed by Cubital Inc. in Israel, started in 1987.

• two commercial machines - Solider 4600 and 5600

• Uses photosensitive polymers, but these are developed using a UV light and a photopolymer
1. photopolymer is developed and hardened by a UV mask that has the pattern for one slice of the part.
2. Unhardened polymer is cleaned away and replaced with wax, that is solidified with a cooling plate.
3. the polymer/wax layer is machined to exact thickness, and coated with a new layer of polymer. (a vacuum is used to remove cut chips)
4. The process continues until done

• The masks are made using a glass plate with electrostatic powder distribution (similar to photocopiers). A slice is used to electrostatically charge a glass plate, electrostatic sensitive powder coats the charged areas, and the mask is complete. After use the glass is cleaned and reused.

• After completion the wax is melted, and the complete part remains. (the wax was used to support work and eliminate supports.)

************ Include SGC figures from pg 60 and 64

• the UV lamp is 4KW and is exposed to the polymer for a few seconds

• a resin applicator spreads the photopolymer across in thin layers

- an aerodynamic wiper is used to remove excess material to a storage reservoir. This material may be reused if not overexposed (?) thus causing a change in viscosity.

- because the toxic resins are used, exhaust fans and dark work cabinets are required.

- Advantages,
  - no need for time consuming post-curing
  - part complexity does not effect speed, however volume does.
  - elimination of postcuring reduces internal stresses, and warping.
  - jobs can be stopped, other jobs run, then the first job restarted at a later time.
  - weights may be inserted at any time to alter the centre of gravity
  - supports are not required
  - models with moving parts can be produced because of the firm holding of work in the process.
  - layers can be milled off if they are found to be in error
  - many parts can be run at the same time

- disadvantages,
  - overexposure of the polymer may increase the viscosity, and make it unusable, thus greatly increasing the volume of expensive polymers used.
  - the resins require that light sealed chambers and toxic material handling procedures be used.
  - the machine is very large
  - machining is noisy
  - maintenance is high, requires supervision
  - very few materials available
  - removal of wax after production is required

- Solider 4600 & 5600
  - 65 (5600) or 120 (4600) seconds per layer
  - 14” by 14” by 14” (4600) or 20” by 14” by 20” (5600) work vol.
  - $275,000US (4600), $400,000US (5600)
  - accuracy 0.1%
  - has been used to produce investment casting

- A selected set of specifications for the Solider 4600 are given below,

Specification	Details
Work Volume	14” by 14” by 14”
Accuracy	0.1% up to 0.020” max.
Flatness	typical 0.006”
Resolution	x-y 0.004”, z 0.004”-0.006”
Smallest feature	x-y 0.024”, z 0.006”
Times	preprocess 0:20-3:00 hrs., postprocess 0:30-3:00 hrs.
Production Rate	120 sec/layer, 35 in.**3/hr.
Input Format	solid formats automatically, 2D with user interaction, CT/MRI voxels, etc.

• A selected set of specifications for the Solider 5600 are given below,

Specification	Details
Work Volume	20” by 14” by 20”
Accuracy	0.1% up to 0.020” max.
Flatness	typical 0.006”
Resolution	x-y 0.004”, z 0.004”-0.006”
Smallest feature	x-y 0.024”, z 0.006”
Times	preprocess 0:20-3:00 hrs., postprocess 0:30-3:00 hrs.
Production Rate	65 sec/layer, 80 in.**3/hr.
Input Format	solid formats automatically, 2D with user interaction, CT/MRI voxels, etc.

65.6 FUSED DEPOSITION MODELLING (FDM)

• Developed by Scott Crump, and Stratasys has been selling the machine since 1991.

• The concept is that material is heated and then in controlled quantities deposited directly on previous layers. Eventually layers are built up to complete the entire part.

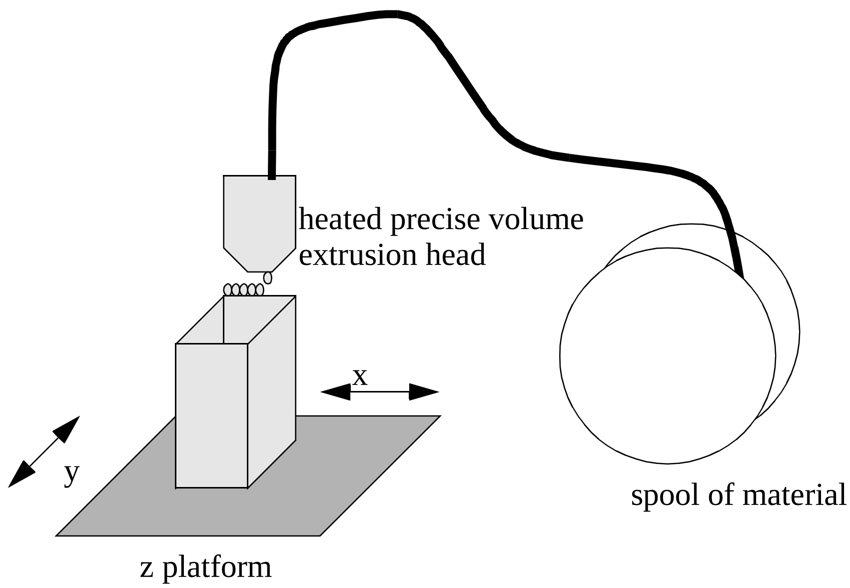
• The materials are available on spools of 1/2 mile in length, at costs from $175(US) to $260(US). The filaments are 0.05”

• As usual the .STL file is sliced into layers, and the slices are used to drive the machine.

• The key to this method is an extrusion head,
  - the material is fed into the head
  - the material is heated until melting
  - the material is then extruded from the tip in controlled quantities
  - the material is wiped on the previous layer

• The extrusion head is moved about the table with an x-y positioning system to deposit material on each layer

• The platform the part is on drops when a layer is complete to allow the addition of a new layer.



machine	Volume	$(US)	comments
FDM 1650	10” by 10” by 10”	115,000	
FDM 2000	10” by 10” by 10”	140,000	faster the 1650
FDM 8000	18” by 18” by 24”	200,000	
Genisys	8”by8”by8”	50,000	polyester
FDM Quantum	23.6”by19.7”by23.6”	350,000	5 times faster then 2000

• materials include
  investment casting wax
  ABS
  polyester
  elastomer

• slice thickness is 0.002” to 0.03”

• material changeover requires a few minutes of “flushing-out’

• Advantages,
- a good variety of materials available
- easy material change
- low maintenance costs
- thin parts produced fast
- tolerance of +/- 0.005” overall
- no supervision required
- no toxic materials
- very compact size
- low temperature operation.

• Disadvantages,
- seam line between layers
- the extrusion head must continue moving, or else material bumps up
- supports may be required
- part strength is weak perpendicular to build axis.
- more area in slices requires longer build times
- temperature fluctuations during production could lead to delamination

• selected specifications for the FDM1000 are,

Specification	Detail
Work Volume	10” by 10” by 10”
Accuracy	0.005”
Thickness/Width	path width 0.010”-0.125”, thickness 0.002”-0.030”
Head Temperature	140°-400°F
Materials	Investment Casting Wax, Machinable Wax, Polyolefin and Polyamide
Machine Dimensions	26” by 34” by 34”
Weight	250 lbs.
Input Formats	STL, 3D surface or solid
Computer Required	SGI Iris
Operating Temp.	50-85°
Power Supply	110 VAC, 12A, 60Hz

• Approximate costs are,

Model	Price
FDM 1650	$100-115,000
FDM 2000	$115-125,000
FDM 8000	$200-220,000
Genisys	$55-65,000

65.7 LAMINATE OBJECT MODELING (LOM)

• Invented by Michael Feygin 1985, marketed by Helisys as LOM 1015 and LOM 2030. Also manufactured by Paradigm and Sparx AB as HotPlot

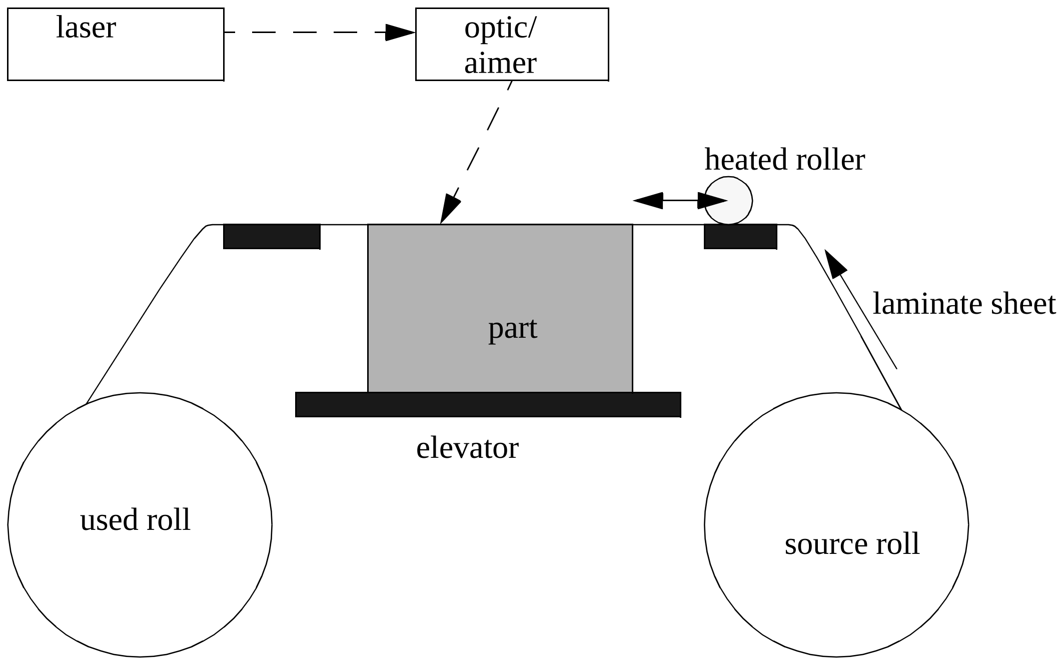
• uses thin sheets of material (most notably paper and polystyrene) that has a heat activated adhesive on one side. Sheets are piled up one at a time, and heat is used to melt sheets together. A laser then cuts the sheet into thin sections that form the slice.

• Slice thickness depends on material and ranges from 0.002” to 0.02”. Materials in use are,
- butcher paper
- plastics
- ceramics
- composites

• The laser uses the typical x-y and optics systems for the laser

• More than one layer can be cut at once, but the accuracy decreases as the number of layers increases.

• As material is cut, it is not removed. Material that is to be discarded is cut into “tiles”. There are chunks of material that will support the part, and are easily removed to recover the part.



• When complete the part is in the middle of a block. Outside there is a “wall” to support the tiles, and in turn the tiles support the parts.

• A heated roller compresses the laminate to the other layers. The thickness is harder to control, so the height of the material is measured each time to ensure accuracy.

• The final part requires careful removal from the tiles, and is finally sealed to keep moisture out, and prevent layer separation.

***************** Include LOM process photos

• The system uses a CO_2 laser, and the cuts are done at varied powers and speeds. Note that these cuts are not done in raster lines such as other techniques

• The other laser positioning systems operate differently, in this case the mirrors are rotated, which is better suited to drawing vectors, as opposed to rasters.

• advantages,
  - no chemical changes, and minimal heating, so the shrinkage is trivial, and stress induced deformation is very small.
  - shrinkage is compensated for
  - no “developing/heating time” is required
  - the laser only has to cut the part outline and hatching, not all the internal area.
  - no supports needed
  - a large variety of materials can be used: butcher paper is \$2/lb for 0.004” thickness
  - the system is inexpensive to maintain

- non-toxic materials
- these machines are well suited to desktop operation

• disadvantages,
- removal of the tiles can be difficult because the laser cuts through the layers, not between them. This requires schemes to weaken material layers that are at a solid/air interface. Cross hatching is used to “burn-out” and weaken materials
- delicate parts can be damaged when removing tiles.
- enclosed volumes will trap the support material
- the material properties change with the direction of the laminate
- a great percentage of the material is wasted
- the surface is rough
- machinability is limited because of delamination
- ventilation is required for fumes when burning
-

• The machine costs are itemized below,

Machine	Cost	Workspace	Comments
LOM 1015	$92,000US	15” by 10” by 14”	
LOM 2030?	$180,000US	32” by 22” by 20”	cooler for laser required
LOM 2030H	$254,000US		

• The laser power is 20-50 W

• Accuracy is +/- 0.002” in x-y and +/- 0.001” in z

• has been used for,
- concept
- design verification- fit/form
- mold production

• time required is hours to days

• wax can be used to add fillets

• to do sand casting
1. build polyurethane molds from the LOM model
2. build polyurethane, or epoxy pattern equipment
3. produce sand molds
4. cast many metal parts (tolerances were in the range of 1/5 to 3/100”)

• plaster casting
1. build rubber, epoxy, or polyurethane plastic molds from LOM model

2. pour rubber pattern from mold
3. produce plaster molds
4. cast up to 100 parts (tolerances in the range of +/- .01” to .02”)

- Investment Casting (one shot only)
    1. Apply sealant to LOM model
    2. Develop a mold using ceramic slurry
    3. place in autoclave to cure ceramic shell
    4. Burn out LOM paper in oven and remove ash

- Indirect Investment casting
    1. make RTV silicone or epoxy mold of LOM part
    2. mold wax pattern
    3. make ceramic mold out of part
    4. use autoclave to melt wax and cure shell
    5. put in oven and burn out wax.
    6. 6. cast part

- making RTV Silicone Rubber Molds
    1. Gating is added to the LOM model
    2. the model is placed in a box and RTV silicone is poured in to cover the model
    3. the silicone is degassed and cured
    4. the silicone mold is split, and the part is remove.
    5. 10 to 30 polyurethane parts can be cast in the mold

- Selected specifications are given for a LOM 1015,

Specification	Detail
Work Volume	14.5” by 10” by 14”
Accuracy	0.010”
Laser	25W CO2, 0.010”-0.015” beam dia., laser is moved, 15”/sec cutting speed, laser chiller optional
Control Computer	IBM PC with special software
Input Formats	STL
Network	Ethernet
Materials	Paper, Polyester, etc., thickness 0.002”-0.020”, material rolls 3”-17” dia., 13.5” width
Machine Size	44” long by 40” wide by 45” high
Power Supply	115VAC, 15A, 60Hz
Environmental	Outside Venting

- Selected specifications are given for a LOM 2030,

Specification	Detail
Work Volume	32” long by 22” wide by 20” high
Accuracy	0.010”
Laser	50W CO2, beam dia. 0.010”-0.015”, laser moved by x-y table, 24”/sec cutting speed, laser chiller required
Control Computer	IBM PC with special software,
Input Formats	STL
Network	
Materials	Paper, polyester, thickness 0.002”-0.020”, on rolls 20” dia, 32” wide
Machine Size	81” long by 60” wide by 57” high
Power Supply	220 VAC, 20A, 60Hz
Environmental	Outside venting

65.8 DIRECT SHELL PRODUCTION CASTING (DSPC)

• Invented by Emanuel Sachs 1989 at MIT

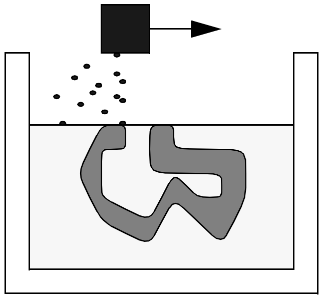
• marketed by Soligen

• Basic process,
1. layer of powder is deposited, spread, and compressed on a pallet.
2. The material for the slice is fused using a print head that moves in a raster and sprays adhesive in required spots.
3. repeat until done.

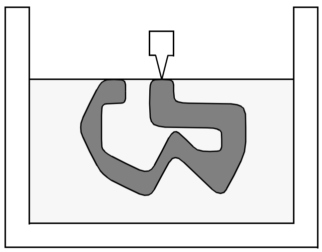
• the unfused powder is not removed, and thus supports the rest of the part

• when complete the powder is removed and reused

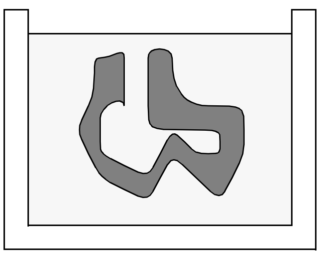
• the result is a shell that can be used in casting. Therefore these parts often include the gating required for the metal flow.



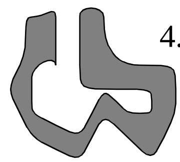
1. powder distribution
   - Aluminum powder is distributed and compressed by a roller



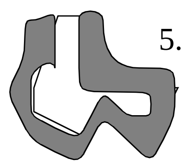
2. Adhesive fusing by printhead
   - operates like a printer, but uses colloidal silica



3. Part complete



4. Part removed



5. Part cast in shell

• advantages,
- produces good castings directly
- the variety of usable common powders is large (using about 320 grit)
    - silicon carbide
    - alumina
    - zircon
    - silica
    - aluminum oxide
- allows tests using metal parts for strength and fit
- eliminates costly time consuming intermediate stages to casting
- can produce very complicated molds
- the mold can be removed from cavities after molding by using a caustic bath. (the rest is simply smashed off)
- many parts can be made at once
- non-toxic materials
- no warping or distortion

- it is faster to spray adhesive than fuse/cut with laser
- final materials only limited by casting

• disadvantages,
    - rough surface finish: details down to 0.175mm; tolerance +/- 0.05mm
    - unbound powder can clog in hidden cavities
    - the printing jet tends to clog.
    - not commercially available yet
    - small work envelope

• work volume is 8” by 12” by 8”

• resolution of print head 0.007”

• cost for alpha machine $200,000US

• Expected machine in 1994 is,
    - $250,000US
    - 20” by 20” by 20”
    - 0.002” resolution
    - 5 min/layer
    - 9 to 20 hours for build

65.9 BALLISTIC PARTICLE MANUFACTURING (BPM)

• Developed by BPM technology

• Sprays material (wax) in 0.002” drops at rates of 12,500 drops per sec to build up slices

• The elevator drops as slices are formed

• Variable slice thickness is set by changing the flow rate

• Part material supports are made from water soluble wax (polyethelene glycol) and are removed after completion by placing the model in water

• The BPM personal modeler is $35,000

• Incremental fabrication is a ballistic particle method developed by Incre Inc. but molten metal is used instead.

65.9.1 Sanders Prototype

• This methods uses two thermoplastic materials the positive having a higher melting temperature. The materials are distributed by a head that will melt and deposit either material (much like an ink jet printer head doing multiple colors). A raster scan is used to build up layers until the final composite part is done. The lower temperature material is melted away to leave the inner part.

• This method is very good for small parts, and produces parts in engineering materials.

• There are two commercially available units,

Model	Cost
MM-6Pro	$59,900
Modelmaker II	$64,900

65.9.2 Design Controlled Automated Fabrication (DESCAF)

• Invented in 1986 by Efrem Fudim

• Marketed by Light Sculpting Inc.

• Uses photomasks of layers to develop sections.

• Exposes the parts to UV light, and develops the photomask

• Requires about 40 sec/layer

• Expected specs.

Machine	Cost	work vol.
LSI-0609MA	$99,600US	6” by 6” by 9”
LSI-1212MA	$129,000US	12” by 12” by 12”
LSI-2224	$159,000US	22” by 22” by 24”
Maskplotter	$25,000	
Postcuring	$10,000	

65.10 COMPARISONS

• An early case study [Rapid Prototyping Report, 1992b] revealed part costs were generally $88 to $344 for a 1.5 by 1.5 by 3 in. speedometer adaptor. The figures are given below, and dollar figures are based on Chrysler labor (Starts with an STL file). The SGC method assumes 35 parts are made at one time, but all figures quoted are for a single part.

Cost/Time	Process				
	STL	SGC	SLS	FDM	LOM
Pre-build Time (hrs.)	0:34	0:21	0:35	4:20	0:46
Pre-build Cost ($)	$38.02	$23.35	$38.69	$288.81	$51.36
Build Time (hrs.)	5:06	10:00	3:00	8:00	9:51
Build Cost ($)	$28.77	$10.05	$31.99	$39.11	$22.49
Post-build Time (hrs.)	1:45	1:00	1:20	0:15	0:25
Post-build Cost ($)	$38.50	$22.00	$29.26	$5.50	$9.24
Maintenance Cost ($)	$24.66	$1.88	$27.40	$7.52	$22.49
Material Cost ($)	$4.00	$31.43	$5.89	$4.00	$3.82
Total	$133.94	$88.70	$199.23	344.94	$109.40

• Costs for machines from other vendors are listed below. Most of these are Stereolithographt units not available in the US because of patents.

Vendor	Model	Cost
Aaroflex	Sl-18-ss-isla	$385,000
Aaroflex	Sl-22-A1-isla	$425,000
Denken Engineering	SLP-5000	15 M yen
Kira Corp	KSC-50	$140,000
Meiko Corp		14.1 M yen
Sony/JSR D-Mec	SCS 1000-D	$500,000
Teijin Seiki Co Ltd	Soliform 500	$450,000
Z Corporation		$50,000
EOS GmbH	Stereos Desktop	DM 250,000
EOS GmbH	Stereos Max-400	DM 580,000
EOS GmbH	Stereos Max-600	DM 700,000
EOS GmbH	Eosint P-350	DM 730,000
EOS GmbH	Eosint M-250	DM 580,000
EOS GmbH	Eosint S-700	DM 1,200,000
DM = $1.75 (US)		
yen =		

65.10.1 References

65.11 AKNOWLEDGEMENTS

• My first exposure to rapid prototyping was from an early report written by Leo Matteo when he was an undergraduate student at Ryerson Polytechnic University

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65.13 PRACTICE PROBLEMS

1. Indicate why (one good and one bad point) the following rapid prototyping approaches are well/poorly suited to the part specified.

    a) Stereolithography for a hollow ball
    b) Selective laser sintering for a door hinge
    c) Solid ground curing for a light bulb
    d) Fused deposition modeling for a hollow box
    e) Laminate object modeling for a complete model of a pyramid with the pharaohs tomb inside

2. In general what common problems are faced by all rapid prototyping techniques?

3. a) Why would a full size engine block be difficult to produce with modern rapid prototyping methods? b) How could the problems in #2a) be overcome by changing the RP technologies?

4. Describe the process of a) Selective Laser Sintering, b) Stereolithography.

5. Sketch a prototype that could be made using Selective Laser Sintering.

66. PROCESS PLANNING

• Process planning is the selection of operation and parameters required to manufacture a part.

• A process plan is a list of operations required to manufacture a part.

• This technique is quite inexact, and never perfect.

• Some strategies that can be used to do process planning are,
  - Technology driven features
  - Most significant feature first

• In general a process plan is put together in pieces, but at all times we will be trying to convert features on the design to operations on the process plan.

• Many of the parameters that effect the process planning decisions are related to a part, and to a process being considered.
  - lead times
  - processes available
  - tolerances
  - feature geometry
  - standard features
  - surface finish/roughness
  - geometry complexity
  - material types
  - material properties
  - part shape
  - largest dimension
  - section thickness
  - length to width ratio
  - hole diameters
  - corner radii
  - quality control
  - quantity produced
  - economic batch size
  - capital costs
  - tooling costs
  - lead time
  - material waste
  - production rate
  - tool life
  - environmental impact

OPERATION SHEET

Part No. *CLP023456-4-92-023* Material *steel 1040*
Part Name *Widget*
Orig. *H.Jack* Changes
Checked *W.H.ElMaraghy* Approved *D.Corrin*

No.	Operation	Machine	Setup	Time (hrs.)
0010	*Saw off and slug 1.75 dia. hole*	*Dept 12. Saw 3*		*.3*
0015	*R'Turn 6.00 dia. stock to 5.210/5.190* *R'Bore 1.75 dia to 2.00* *F'Bore 2.00 to 2.005/2.015*	*G.E. Turn Lathe*	*Hold in counter centrifugal Chuck*	*1.2*
0025	*Deburr all edges*			*5 mins.*

66.1 TECHNOLOGY DRIVEN FEATURES

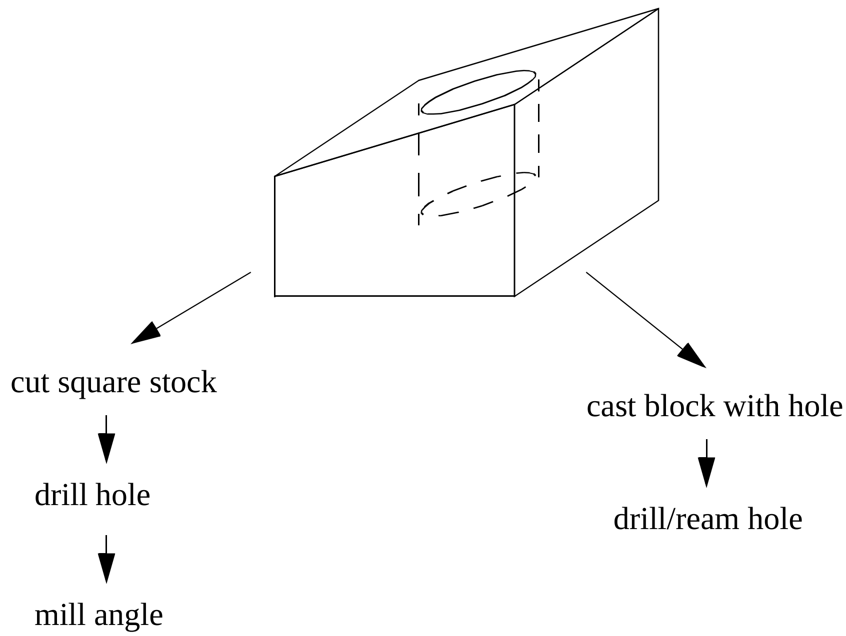
• Some parts have features that are so advanced or specialized that they can only be produced with one technology. Consider a ferrous part with a high strength that requires a specific heat treating operation.

• The general approach is to start at the end of the process plan, and work backwards. When the design features left are normal

66.2 MOST SIGNIFICANT FEATURE FIRST

• Generally we can identify the most significant geometry. Some things to look for are,
  - the features are all cut from a base piece - cutting
  - there is a natural parting line - welding/molding/casting
  - features seem to be stuck-on a base piece. - assembly/molding/casting
  - large/small mass
  - material

• An example of this is an angled block with a hole,



• Identifying significant features can be difficult, but some experience can help.

• Large volumes of metal make parts hard to handle,

>1000 lbs.	Sand Casting (450 tons)
> 100 lbs	Investment casting (110 lbs.) Hot forging (500 lbs.)
> 10 lbs	Die casting (35 lbs.) Structural foam molding (50 lbs.)

• Thin walls can be difficult to manufacture and will collapse under force,

< 0.25 in.	Sand Casting (0.125”)
< 0.1 in.	powder metallurgy (0.06”) Investment casting (0.025”) Die casting (0.025”) Injection molding (0.03”) Structural foam molding (0.09”) Blow molding (0.015”) Rotational molding (0.06”)
< 0.01 in.	Hot extrusion (1.5% of circumscribed dia.) Spinning (0.004” sheets) Sheet Metal Stamping Bending (0.001” sheets)
< 0.001 in.	Electroforming

• Small hole diameters can be difficult to produce,

< 0.25 in.	
< 0.1 in.	powder metallurgy (0.06”) die casting (0.04”) Cold heading (0.06”)
< 0.01 in.	machining Electrochemical machining (0.01”) Electrodischarge machining (0.002”)
< 0.001 in.	Electroforming

• Tolerances can be difficult to maintain.

<0.01in.	rotary swagging (0.003”) Hot Extrusion (0.005”) turning (0.001”) milling (0.002”) drilling (0.008”) reaming (0.001”) electrochemical machining (0.001”) electro discharge machining (0.001”) investment casting (0.002”) die casting (0.002”) injection molding (0.003”) structural foam molding (0.003”) impact extrusion (0.002”)
<0.001in.	boring (0.0005”) broaching (0.0005”) grinding (0.0008”)
<0.0001in.	
<0.00001in	

• Surface finish can be difficult to obtain, (micro-inches),

< 62.5	boring (32) sheet metal stamping/boring (32) thermoforming (60) spinning (32) die casting (32) cold heading (32)
< 32	impact extrusion (20)
< 16	grinding (8) electrochemical machining (8) electo discharge machining (8) injection molding (8)
< 8	

• Difficult to produce features have preferred processes,

tapers	rotary swagging turning
complex cross section	hot extrusion
round parts	turning
prismatic shapes	milling
hardened materials	electrochemical machining electro discharge machining
complex geometry	powder metallurgy electrochemical machining electro discharge machining sand casting investment casting injection molding die casting

weak materials	electrochemical machining electrodischarge machining
thin walls	sheet metal stamping/bending thermoforming metal spinning hot extrusion blow molding
internal features	sand casting

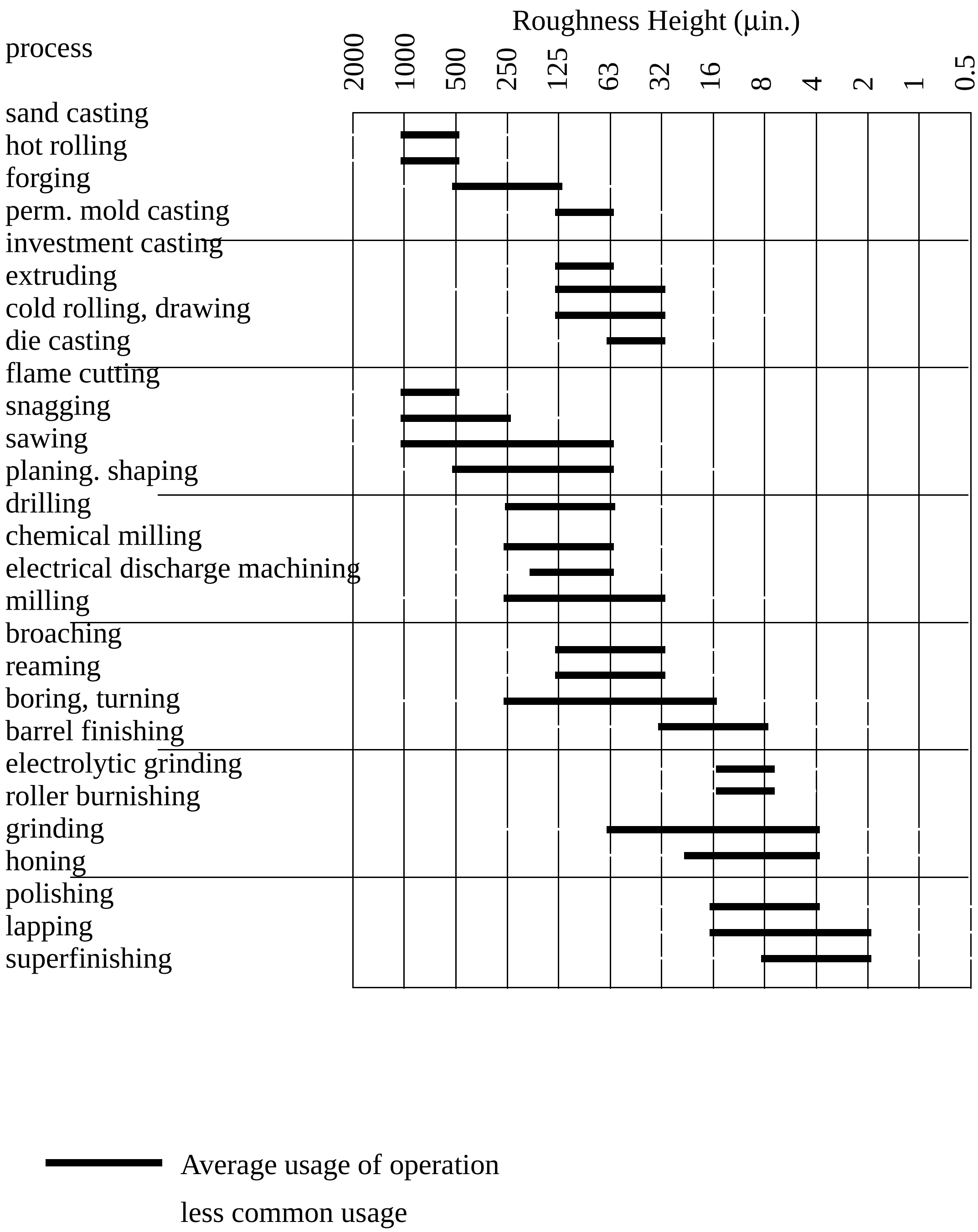
XXXXXX

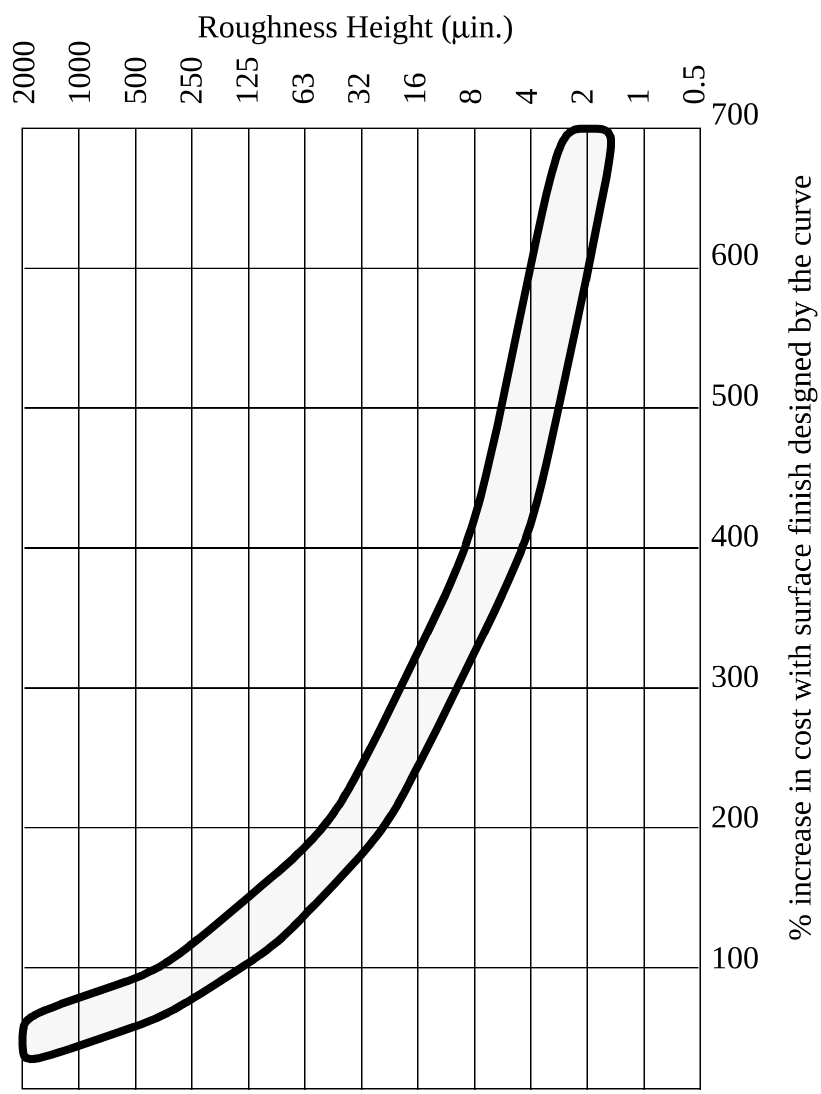
• Materials tend to dictate suitable processes,

Cast Iron	casting, powder metallurgy, machining, electrochemical machining, sand casting
Carbon Steel	powder metallurgy, rotary swagging, hot extrusion, machining, electro discharge machining, sheet metal stamping/bending, spinning, sand casting, investment casting, impact extrusion, cold heading, hot forging
Alloy Steel	powder metallurgy, rotary swagging, hot extrusion, machining, electro chemical machining, electro discharge machining, sheet metal stamping/bending, spinning, sand casting, investment casting, impact extrusion, cold heading, hot forging
Stainless Steel	powder metallurgy, rotary swagging, hot extrusion, machining, sheet metal stamping/bending, spinning, sand casting, investment casting, cold heading, hot forging
Aluminum and Alloys	powder metallurgy, rotary swagging, hot extrusion, machining, electro discharge machining, sheet metal stamping/bending, spinning, sand casting, investment casting, die casting, impact extrusion, cold heading, hot forging
Copper and Alloys	powder metallurgy, rotary swagging, hot extrusion, machining, electro chemical machining, electro discharge machining, sheet metal stamping/bending, spinning, sand casting, investment casting, die casting, impact extrusion, cold heading, hot forging

Zinc and Alloys	rotary swagging, hot extrusion, machining, sheet metal stamping/bending, spinning, sand casting, die casting, impact extrusion
Magnesium and Alloys	rotary swagging, hot extrusion, machining, sheet metal stamping/bending, spinning, sand casting, investment casting, die casting, impact extrusion, hot forging
Titanium	powder metallurgy, hot extrusion, machining, electro chemical machining, electro discharge machining, impact extrusion, hot forging
Thermoplastics	machining, thermoforming, injection molding
Thermosets	machining, injection molding, structural foam molding, blow molding, rotational molding
Nickel and Alloys	powder metallurgy, rotary swagging, machining, electro chemical machining, electro discharge machining, sheet metal stamping/bending, spinning, sand casting, investment casting, impact extrusion, cold heading, hot forging

• We can use a comparative graph of surface roughness to pick a process.


Roughness Height (µin.)
process
2000
1000
500
250
125
63
32
16
8
4
2
1
0.5
sand casting
hot rolling
forging
perm. mold casting
investment casting
extruding
cold rolling, drawing
die casting
flame cutting
snagging
sawing
planing. shaping
drilling
chemical milling
electrical discharge machining
milling
broaching
reaming
boring, turning
barrel finishing
electrolytic grinding
roller burnishing
grinding
honing
polishing
lapping
superfinishing
Average usage of operation
less common usage



66.3 DATABASE METHODS

• When process planning we may use historical data to select operation parameters.

• Metcapp basically does this, it uses sampled data, and then interpolates to find a suitable speed and feed for a cut.

• A sample of a table of roughness measurements is given below [Krar],

Tool	Operation	Material	speed	feed	tool	cutoff	Range	surface RMS
cutoff saw	sawing	2.5” dia. Al	320’/min		10 pitch saw	0.030”	1000	300-400
shaper	shaping flat surf.	machine steel	100’/min	0.005”	3/64” rad. HSS	0.030”	300	225-250
vertical mill	fly cutting	machine steel	820 rpm	0.015”	1/16” rad. stellite	0.030”	300	125-150
horizontal mill	slab milling	cast Al	225 rpm	2.5 “/min	4” dia HSS slab cutter	0.030”	100	40-50
lathe	turning	2.5” dia. Al.	500 rpm	0.010”	R3/64” HSS	0.030”	300	100-200
	turning	2.5” dia. Al.	500 rpm	0.007”	R5/64” HSS	0.030”	100	50-60
	facing	2” dia. Al.	600 rpm	0.010”	R1/32” HSS	0.030”	300	200-225
	facing	2” dia. Al.	800 rpm	0.005”	R1/32” HSS	0.030”	100	30-40
	filing	0.75” dia. steel	1200 rpm		10” lathe file	0.010”	100	50-60
	polishing	0.75” dia. steel	1200 rpm		#120 cloth	0.010”	30	13-15
	reaming	Al.	500 rpm		3/4” dia HSS	0.030”	100	25-32
surface grinder	flat grinding	machine steel		0.030”	60 grit	0.003”	10	7-9
cutter/tool grinder	cyl. grinding	1” machine steel		manual	46 grit	0.010”	30	12-15
lapping	flat lapping	.87”x5.” tool steel		manual	600 grit	0.010”	10	1-2
	cyl. lapping	0.5” dia. tool steel		manual	600 grit	0.010”	10	1-2

66.4 MANUFACTURING VOLUMES

• When we are planning operations we must consider the economy of scale.

• If we are producing large volumes, we may want to produce tooling (expensive), but amortize the costs over thousands of parts (less expensive). Examples of this include,
- injection molds for thermoplastics
- molds for wax, to make investment casting molds
- progressive dies

- etc.

66.5 STANDARD PARTS

• Purchased components are typically well designed and inexpensive.

• When you do not have experience designing or manufacturing a certain component, and volumes are low, it may not be possible to produce components at a lower cost than they can be produced.

• These parts must still be considered in the process plans so that they are orders, and arrive in suitable forms.

66.6 PRACTICE PROBLEMS

1. A block of metal 5” by 5” by 5” will be milled to 5” by 5” by 4” and then will have two separate holes drilled 2” deep. The hole will be finished with a reamer.

   Part: - Mild Steel
   Drilling:- High speed steel
   - 15/32” diameter
   - C.S. = 80 ft/min.
   - feed = .010” per revolution
   - setup time = 5 min. per part
   - cost is $40.00 per hour

   Reaming:- Carbide Steel
   - 1/2” diameter
   - C.S. = 60 ft./min.
   - feed = .015” per revolution
   - setup time = 2 min. per hole
   - cost is $45.00 per hour

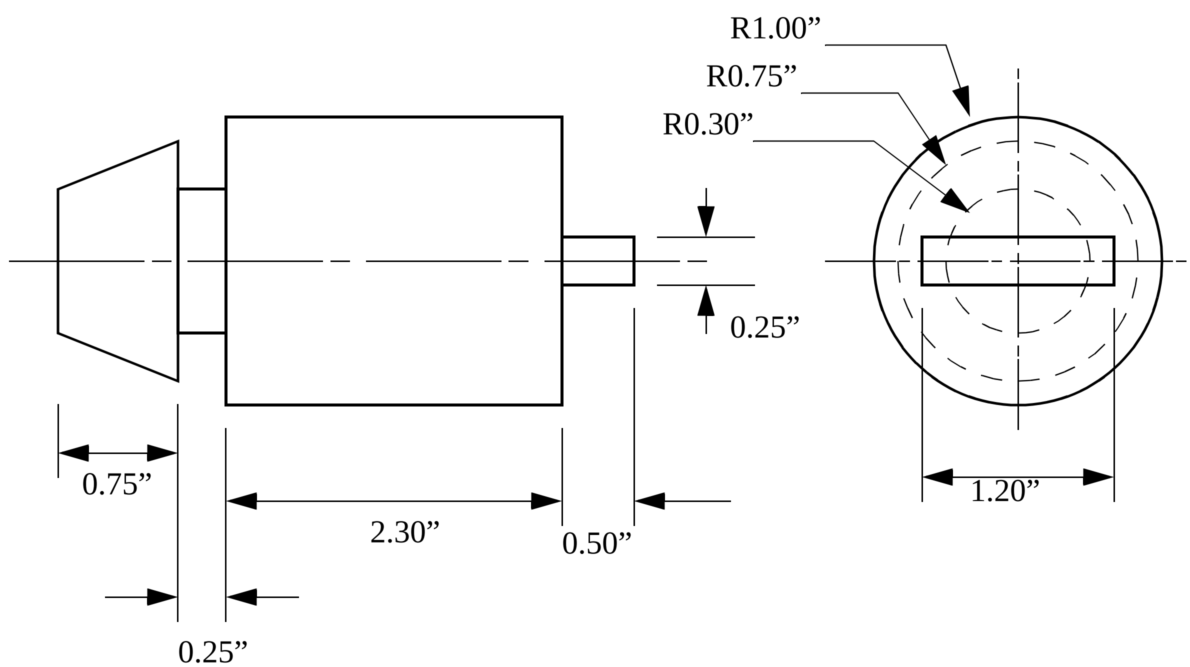
   Milling:- High speed steel
   - C.S. = 100 ft./min.
   - cutter diameter = 1”
   - 10 teeth with a tooth load of .004” per tooth
   - setup time = 1 min. per part
   - cost is $47.50 per hour

   a) Estimate the machining time required to make 50 parts.
   b) Estimate the cost of the 50 parts.
   c) Estimate the machine horse power required for the drill, reamer and the mill.

2. Calculate the machine tool spindle speeds for the following:

a) Milling with a tungsten carbide tipped face cutter on a stainless steel work piece. C.S. = 65 m/min., cutter dia. = 150mm.
b) Drilling with a High Speed Steel drill in Machine Steel work, with C.S. = 70 ft./min., and a drill diameter of 19/32”
c) Turning on a lathe with a High Speed Steel tool in a mild steel work piece. Surface cutting speed = 100 ft./min., and a workpiece diameter of 2.75”
d) Milling with a High Speed Steel cutter in tool steel work with a cutter speed of 60 ft./min., and a cutter diameter of 3/4”.

3. The part below has three turned diameters, on one end there is a square tang that has been milled. The part is made of aluminum. (Note: R indicates radius)



a) Write a process plan that describes the operations necessary to produce the part.
b) If the milling cutter is a 1/2” diameter end mill with 6 teeth, determine a reasonable feed and speed for cutting the tang.
c) What are reasonable speeds and feeds for turning the part for rough and finish turning? (Note: pick one cut for your calculations)

ans. a) 0010 Cutoff stock with dia. 2 1/4” by 4”
0020 Mount 0.75” in 3 jaw chuck
0030 Face end and turn down to 2” dia. for 2.8”
0040 Turn in chuck and face to length
0050 Cut the taper with a taper cutting attachment
0060 Use a slot cutter to cut the 0.25” slot 0.4” below the taper
0070 Mount upright in vise in mill
0080 Use endmill to cut around the tang

b)

$$CS = \left(\frac{500 + 1000}{2}\right) = 750\frac{\text{ft}}{\text{min}} \qquad fpt = 0.011\text{in}$$

$$RPM = \frac{12CS}{\pi D} = 5730 \qquad F = fpt(teeth)RPM = 378\frac{\text{in}}{\text{min}}$$

c) Rough / Finish

Rough:

$$CS = 200\frac{\text{ft}}{\text{min}}$$

$$F = \left(\frac{0.015 + 0.030}{2}\right) = 0.023\frac{\text{in}}{\text{rev}}$$

$$RPM = \frac{12CS}{\pi D} = 382$$

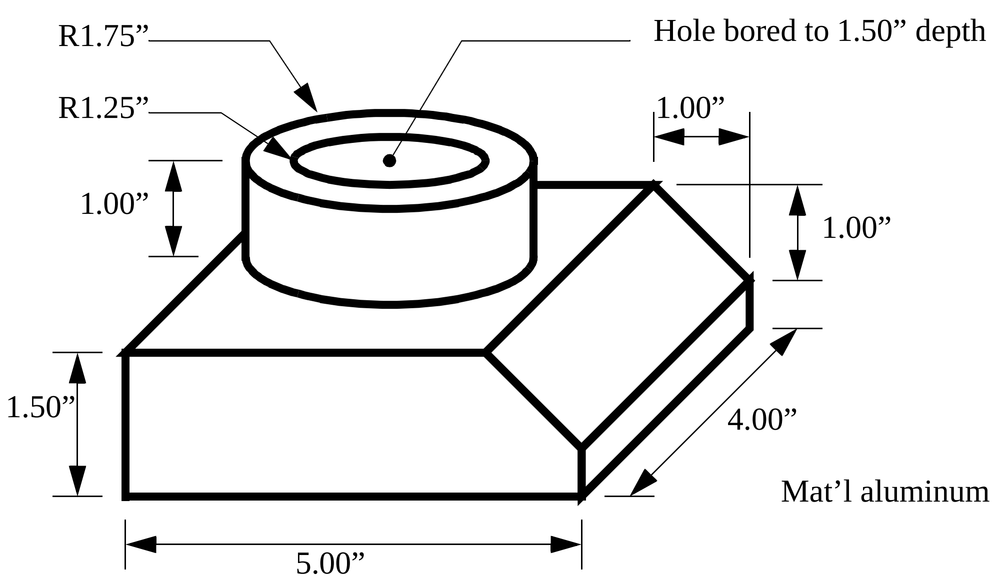
Finish:

$$CS = 300\frac{\text{ft}}{\text{min}}$$

$$F = \left(\frac{0.005 + 0.010}{2}\right) = 0.008\frac{\text{in}}{\text{rev}}$$

$$RPM = \frac{12CS}{\pi D} = 573$$

4. Develop a process plan for the part below. You should include speeds, feeds and times. Hint: The part will be easy to make if a combination of milling, drilling and turning is used.



66.6.1 Case Study Problems

66.6.1.1 - Case 1

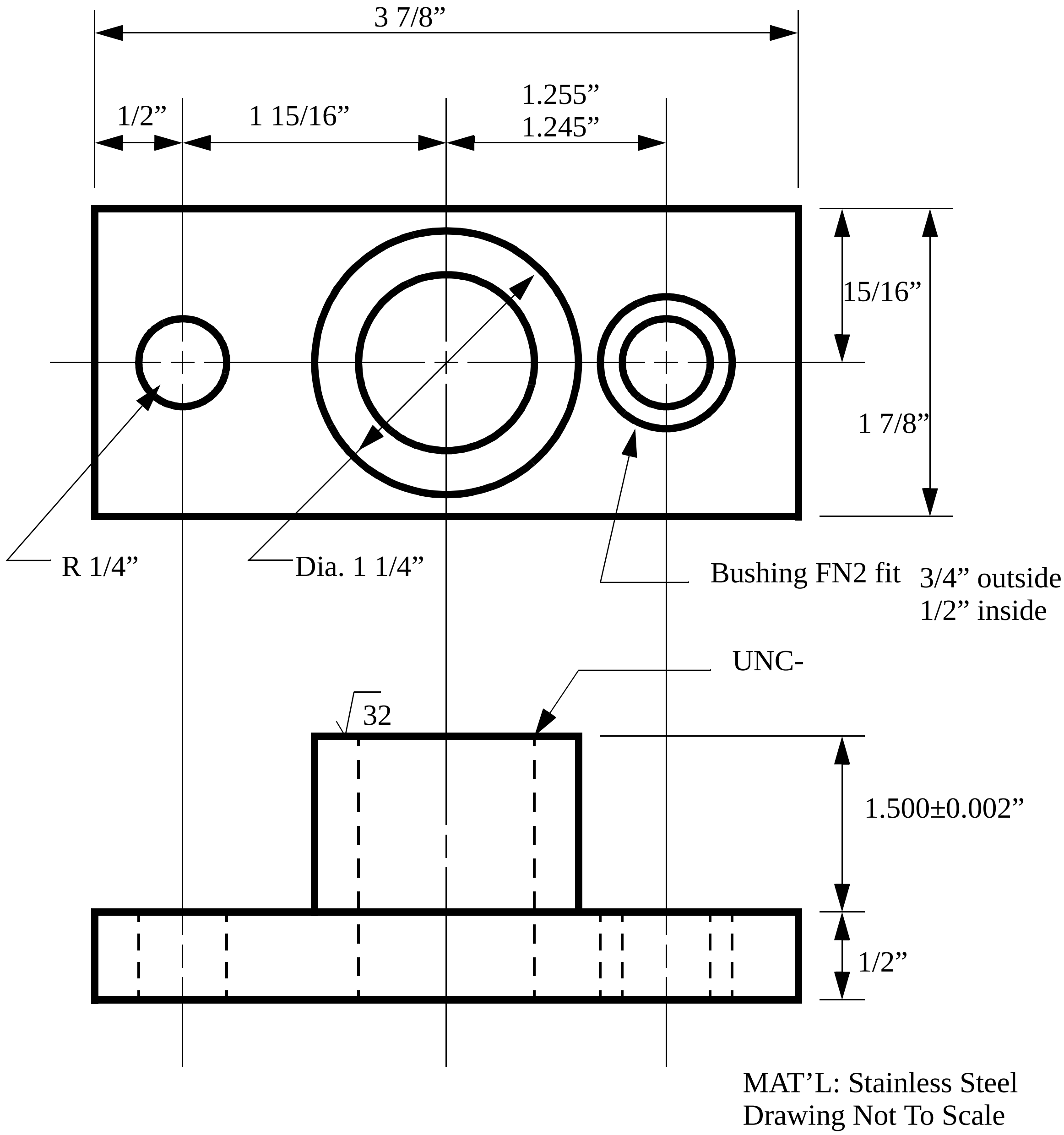
OVERVIEW: You have just been hired as a manufacturing engineer by Sports Wares and Equipment Technology (SWET) Inc., a small company. The engineer you are replacing was working on a new product but had to resign for family reasons. On your first day there are a number of desperate problems that have to be examined, and the company is counting on the quality of the answers you provide. To make your life harder, your boss made it quite clear that your reputation is on the line and small mistakes may be very costly.

YOUR ROLE:You are to follow the day of the manufacturing engineer, and interact with others to get the job done right.

THE FACILITIES: As the manufacturing engineer it is your job to direct the setup of equipment for the new product. At present you know about the following machines, and their hourly costs.

lathe ($30/hr)
mill ($40/hr)
stock room ($20/hr)
cutoff saw ($30/hr)
drill ($25/hr)

THE NEW PRODUCT: The product you are working on is a mounting bracket for sports equipment. As can be seen in the figure below the bracket involves a rectangular base plate with one hole, one press fit bushing and one threaded shaft. The drawing is not yet final, and the design engineer needs a couple of answers before he can complete the drawing. In addition, the people in production are asking you questions.



YOUR DAY:

9:10am Joseph Blough drops by your office and explains he has just been hired in production and is not sure how to read a micrometer. a) He asks you to draw an example of a simple micrometer reading 0.235”. b) He then asks why a bench micrometer has a larger thimble.

9:20am Ian Specter in Quality Control phones you and explains he is ordering metrology equipment and asks you to recommend inspection techniques for a) the overall height tolerance, b) the locational tolerance between the centre of the thread and the bushing, and c) the surface roughness.

9:35am Ian calls back and says that all of your earlier suggestions were too expensive and asks for alternatives.

9:55 am Pete Rout in engineering calls and asks how the surface finish specified on the drawing impacts production and quality control. You mention it is not very specific and a) suggest a more specific symbol. You also check your old MEC015 notes and see a chart of surface roughness for different manufacturing processes. You use this to b) suggest a more appropriate surface roughness value.

10:20am Anne Nuther drops by your office and seems concerned about the dimensions and tolerances of the bushing and hole in the part. You quickly a) provide the dimensions and tolerances for both.

10:40am Wyoming Knott in maintenance left a message requesting instructions for where to place the machines for the new product. You decide that before you can do the layout you need to determine the required production steps. Luckily you found a partially completed process plan to start with. You decide to a) complete the process plan and b) calculate all required machine settings, times, tools and costs.

a)

Step #	Description	Machine	Parameters/tools/etc	Time	Cost
0010	get 2x1 3/4” square bar stock	none	none	5 min	$1.67
0020	cut to 4” length	cutoff saw	none	5 min	$2.50
0030	mill off to 3 7/8”	mill			
0040	mill width to 1 7/8”				
0050	mill height to 1.5”				

11:30am Phillip Etup in shipping sends a memo saying that they will be testing the bushings that arrived this morning (it seems that your predecessor ordered ahead). They want to know a) if the n=50, c=1 plan from before will give them an AQL of 1% with a producer’s risk of 5%?

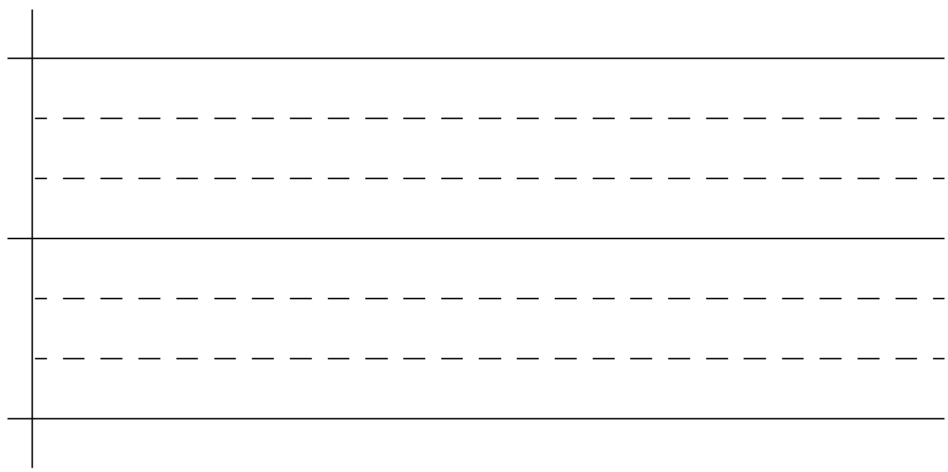
1:15pm Norman Alguy calls and says that the cutting parameters for step 0030 in the process plan look too high for the 10hp mill. If the mill has a 1/4hp idle power and is 95% efficient, a) is it sufficient for the cuts?

2:20pm Anne drops by again to discuss the cutting conditions in your process plan. When they tried the same type of process on the lathe previously, they got a tool life of 1 hour at 500 fpm and 2 hours at 300 fpm. a) How long should the tool last for the proposed process plan?

2:45pm You are looking over the drawings and decide to b) check the capabilities of the drilling process to see if it can locate the 1.245” to 1.255” tolerance. You pull out the old data for a similar bracket that was produced before, and a) construct an X-bar chart to verify the tolerance.

Date:	Measured Values
March 18	1.637, 1.639, 1.638, 1.636
March 19	1.639, 1.640, 1.638, 1.641
March 20	1.642, 1.643, 1.639, 1.642
March 21	1.639, 1.645, 1.643, 1.644
March 22	1.638, 1.644, 1.644, 1.641
March 25	1.636, 1.638, 1.638, 1.636
March 26	1.640, 1.639, 1.642, 1.635
March 27	1.645, 1.643, 1.643, 1.643
March 28	1.636, 1.641, 1.641, 1.638
March 29	1.643, 1.638, 1.645, 1.640

a)



66.7 REFERENCES

Ullman, D.G., The Mechanical Design Process, McGraw-Hill, 1997.