10

Assembly

The assembly of parts and subassemblies to form a product of desired functionality may involve a number of joining operations, such as mechanical fastening, adhesive bonding, and welding. Although assembly processes are not value-adding operations and are commonly seen as necessary but "wasteful" tasks, most of today's products are not manufacturable as single entities. Complexities of products range from a few parts in a piece of furniture to several million parts in commercial aircraft. Thus while some products are passed on to customers as a collection of individual parts for their assembly by the user, with an incentive of reduced price, most products have to be assembled prior to their sale because of either their complex and long assembly process or the specialized tools needed for their joining that are not usually owned by the perspective customers.

Since an assembly process may add significant cost to the fabrication of a product, different manufacturing strategies have been adopted over the past century for increased assembly efficiency (Chap. 1). These cost-cutting measures have included the use of mass production techniques for reduced setup and fixturing costs, as well as specialization of human operators on one or two specific joining tasks; the use of automation for highly repetitive operations; and more recently the use of modular product design for simplification of assembly.

Assembly relies on the interchangibility of parts concept introduced in the mid-1800s. Individual parts' dimensions must be carefully controlled, within their tolerance levels, so that they can be assembled without further rework during their joining. This is a paramount issue in the batch production of goods (i.e., more than one of a kind) and even more important when in the future individual components that wear out must be replaced with off-the-shelf parts. Systems operating at remote locations requiring replacement parts cannot be expected to be returned to a service location for custom fitting of broken or worn parts.

Design for assembly was discussed in Chap. 3 in the context of minimizing cost, satisfying disassembly requirements for maintenance and repair, and even in the context of being environmentally friendly. It was argued that (1) minimization of parts would reduce assembly cost, (2) reduction of permanent joints would ease maintenance, and (3) lesser variety in materials would facilitate recycling.

The objective of this chapter is to address a variety of representative methods for different types of joining operations available to a manufacturer in the fabrication of multicomponent products. These include mechanical fastening, adhesive bonding, welding, brazing, and soldering. Automation issues pertinent to these processes will be briefly discussed in their respective sections. The chapter will be concluded with a detailed review of two specific assembly applications: automatic assembly of small mechanical parts and automatic assembly of electronic parts.

10.1 MECHANICAL FASTENING

Joining of mechanical components through fasteners (screws, bolts, rivets, etc.) is most desirable when future disassembly of the product is expected for maintenance, or when other joining techniques, such as welding or adhesive joining, are not feasible. Several factors affect the number, type and locations of fasteners used in assembling two or more parts: strength of the joints (tensile or compression), ease of disassembly, and appearance.

The location and number of fasteners to be used in a mechanical joint is primarily a function of the strength level we wish to achieve, subject to geometrical constraints (e.g., minimum wall thickness, distance from edge, and potential creation of stress concentrations). The strength of such joints can normally be calculated analytically (for example, through the area of contact of the number of threads on a fastener). Though, in some cases, empirical methods may have to be employed for more reliable estimations.

Product appearance also influences the locations of the fasteners and their types. However, we must be very conscious of ease of assembly and disassembly when making such placement decisions. Designers and

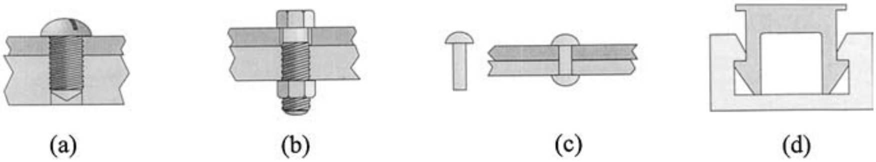


FIGURE 1 Mechanical assembly using (a) a screw, (b) a bolt, (c) a rivet, and (d) a snap-fit joint.

manufacturing engineers must not place fasteners at hard-to-reach places simply for aesthetic purposes, especially if the product is to be assembled by the customer, who may not have a large variety of tools at his or her disposal for fastening.

Mechanical fasteners can be mainly categorized as threaded fasteners, (nonthreaded) rivet-type fasteners, snap-fit fasteners, and interference-type fasteners (Fig. 1). Threaded fasteners can be further divided into two types: self-tapping screws, which do not require the parent component to have already been drilled and tapped, and bolts (and some screws) that either require threads in one (or both) of the parts to be assembled or utilize nuts.

10.1.1 Threaded Fasteners

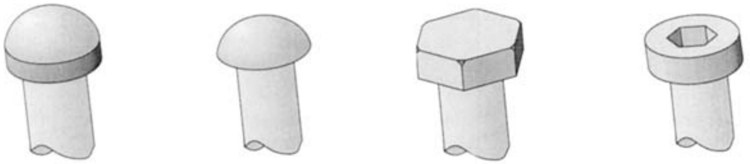
Although screws and bolts may be fabricated in a variety of sizes and shapes, due to interchangeability requirements, designers should utilize standard fasteners, as opposed to requiring special-purpose screws or bolts at (relatively) high costs.

Tension fasteners are available in a number of different head styles, each suitable for a specific task. The two most common ones are briefly reviewed below (Fig. 2).

Pan and truss heads: Both of these head shapes are very popular and come in a variety of drive types (Phillips, Robertson, etc.). Although the truss head normally has a larger bearing area, both types of screws will fail first in the threaded area, as opposed to the head.

Hex head: Such screws have hexagonal external head shapes, though some may have hexagonal internal, socket-drive shapes. They are characterized by their large load-carrying ability, as well as the readily available (industrial) tightening tools. Socket screws with hex drives are normally used for high-strength and high-tolerance applications.

Compression fasteners normally are setscrews that are headless. They are utilized to locate and immobilize one part with respect to another.



Pan head Truss head Hex head (external) Hex head (internal)

FIGURE 2 Screw and bolt heads.

Common setscrew point shapes include the cone point, oval point, flat point, and dog point (Fig. 3).

Although most threaded fasteners are fabricated using a cold-forming operation (Chap. 7), some are machined on dedicated, specialized automatic thread-cutting lathes (Chap. 8). Steel is the most commonly used material for fasteners due to its high strength, good resistance to environmental conditions, and low cost. Some nonferrous fastener materials include brass, bronze, aluminum, and titanium. Due to its high strength-to-weight ratio, titanium fasteners are often utilized in aerospace and sports assemblies, where higher costs are not prohibitive.

Fastener corrosion is the most problematic issue in mechanical assembly and presents users with high maintenance costs (e.g., bolts used in automobile assemblies, especially those used in corrosive environments, such as Canada and Northern European countries). Two common corrosion protection mechanisms are sealing (using plastic- and rubber-based sealant) and electroplating. Zinc, cadmium, nickel, copper, tin, and brass are the most frequently utilized plating materials. Electroplating of threaded fasteners (typically, about 0.01 mm) is a complex process and must be carefully planned for in dimensioning of holes and threads. For example, during electroplating, coated material tends to build up more on the thread "crests" (peak of the thread) and less in the "roots."

Flat point Oval point Cone point Dog point

FIGURE 3 Setscrew geometries.

10.1.2 Rivets

Riveting is a highly effective joining process for the fastening of two segments with a permanent joint. Permanency implies that the only way of removing the joint for disassembly is by destroying the joint. Riveting is very commonly used in the joining of thin-walled structures, such as the fuselages and wings of aircraft.

The riveting process comprises two primary operations: Placement of the (unthreaded) rivet in the hole and deforming the headless end of the rivet (normally through an "upsetting" operation) to form a second head and thus a tight connection. The four primary rivet geometries are shown in Fig. 4. As with threaded fasteners, the designer must choose the minimum number of rivets (not to overfasten) and place them optimally to avoid stress concentrations, which is especially critical in thin-walled parts.

Riveting materials include:

Low- and medium-carbon steels: The majority of rivets (above 90%) are made of such steels for their low cost, high strength, and easily formable characteristics. Typical applications include automotive assembly, photographic equipment, home appliances, and office hardware.

Copper alloys: Rivets of this material are used for appearance, good electrical conductivity, and corrosion resistance. Typical applications include electrical assemblies, luggage, and jewellery.

Aluminum: Rivets of this material have the lowest cost, a bright appearance, and corrosion resistance. Typical applications include transportation equipment, lighting fixtures, storm windows and doors, and toys.

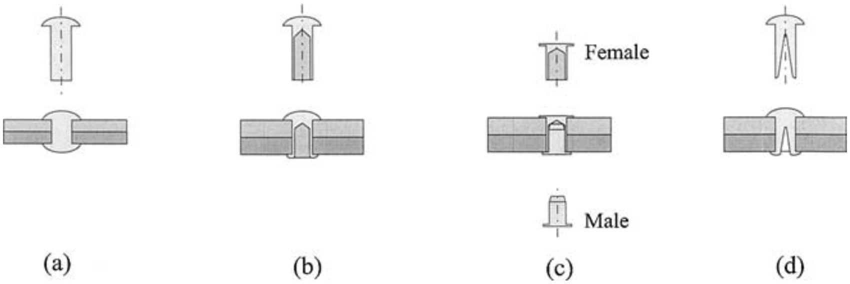


FIGURE 4 Rivet geometries: (a) solid, (b) tubular, (c) compression, and (d) split (or bifurcated).

10.2 ADHESIVE BONDING

Adhesives can be utilized for the joining of most engineering materials: metals, plastics, ceramics, wood, and paper. The joining process involves the placement of an adhesive filler material between the surfaces of two segments of a product (adherents) and the subsequent curing of the adhesives using an initiating mechanism: applications of heat and mixing of two or more reactive components. Some adhesives employ a solvent that evaporates or is absorbed by the adherents that are joined and leaves behind a dry hardened adhesive layer. The resultant joint is permanent and frequently cannot be broken without damage to one or both parts.

Adhesives can be traced back to the gluing of furniture and the use of sealings in a variety of forms in ancient civilizations. Their use in modern times, however, only became widespread with the availability of (organic) monomers at the end of the 19th century and the beginning of the 20th, accelerating after the 1940s. The first use of adhesives in manufacturing was in the bonding of load-bearing aircraft components during the 1940s. Since then, they have been used in the machine-tool industry, the automotive industry, the electronics industry, the medical industry, and the household products industry.

Some advantages of adhesive bonding are

Joining of dissimilar materials: Different materials or similar materials with different thermal characteristics (e.g., thermal-expansion coefficient) can be adhesive bonded.

Good damping characteristics: Adhesive bonded assemblies yield good resistance to mechanical vibration, where the adhesive acts as a vibration damper, as well as resistance to fatigue.

Uniform stress distribution: Broader joining areas yield better stress distribution, allowing the use of thinner assembly components and resulting in significant weight reductions.

Thermal and electrical insulation: Adhesives provide electric and thermal insulation, as well as resistance to corrosion.

Niche application: Adhesive bonding can be used in the joining of parts with complex shapes and different thicknesses that do not allow the use of other joining processes. It can also be used to yield visually attractive products with no visible joints or fasteners.

Naturally, as do other processes, adhesive bonding suffers from numerous drawbacks: parts' surfaces must be carefully prepared to avoid contamination; the joints can be damaged in the face of impact forces and weakened significantly at high temperatures (>200°–250°C); and actual bonding strength may not be accurately verifiable (i.e., a quality control problem). In the following subsections, some of these issues will be briefly addressed.

10.2.1 Joint Design and Surface Preparation

The first step in joint design for adhesive bonding is to understand how adhesives behave under mechanical loading. Tensile loads that may induce peeling or cleavage must be avoided owing to low cohesive strength of adhesives. In contrast, adhesive joints can resist high shear and compression loads, when the joint overlap area is sufficiently large to allow distribution of the applied load. However, high pure shear forces applied for long periods of time may eventually damage the joint.

Empirical data have shown that there is an upper limit to the degree of overlapping of the joints for increased load carrying. Beyond a certain limit, one cannot increase the strength of a joint simply by increasing the length of the overlap. In reference to joint thickness, although engineering intuition

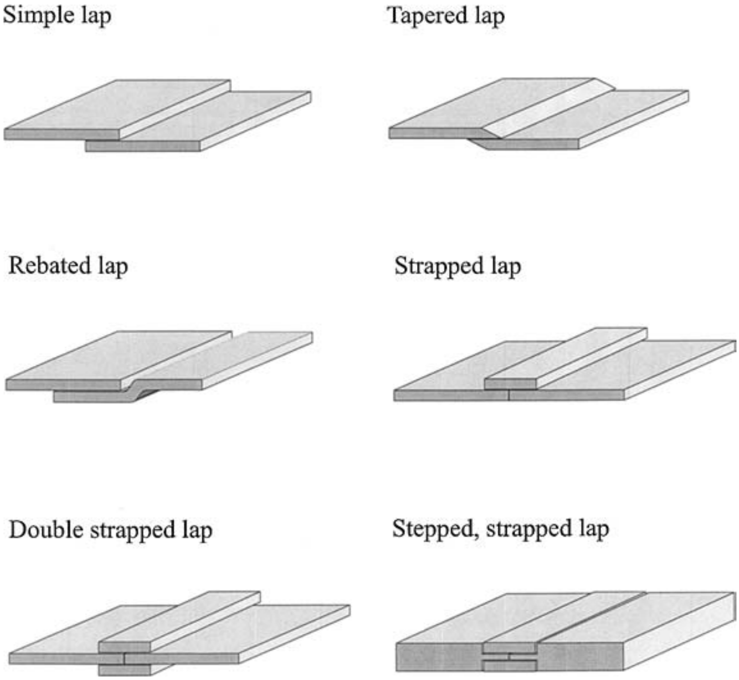


FIGURE 5 Adhesive bonding lap joints.

would advocate the minimization of bond thickness, several studies have shown that some level of increase may actually strengthen the joints.

Most adhesive bonding joints are of the lap-joint type and its variants, some of which are shown in Fig. 5. The simple lap joint requires a toughened adhesive that will not experience a brittle failure due to distortions occurring under shear loading. Otherwise, the geometry of the joint or its configuration, through the addition of third-party segments, must be varied for optimal distribution of loads.

Butt joints (end-to-end contact) are normally viewed as poor forms of adhesive bonding, unless large contact areas are created. Some design guidelines for good adhesive bonding are illustrated in Fig. 6.

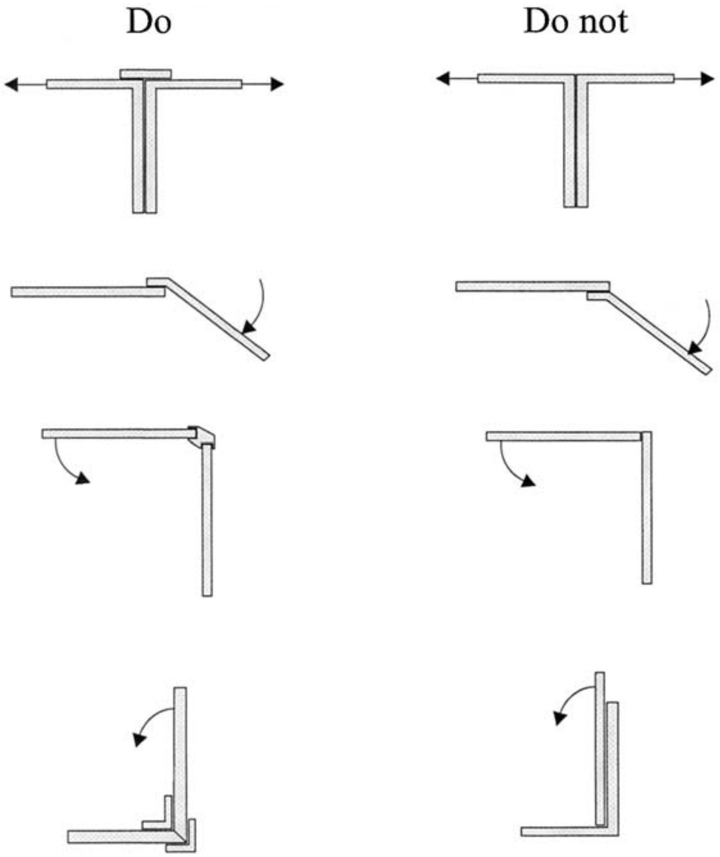


FIGURE 6 Guidelines for adhesive bonding.

Surface preparation is the most important step in adhesive bonding. Contaminants present on the adherents poorly affect wetting and cause premature failure of the joint. There are three common techniques for surface cleaning: solvent degreasing through wiping or vapor degreasing, chemical etching or anodizing, and the use of surface primers. Naturally, the optimal technique(s) selected for surface preparation is a function of the materials of the adherents. However, all surface preparation activities, regardless of adherents' materials, must be quickly followed by the deposition of the adhesive and subsequent bonding operation.

10.2.2 Adhesives and Bonding Techniques

Adhesives can be broadly classified into two groups: organic and inorganic. The former can be further classified into natural (e.g., dextrin, rubber) and synthetic (e.g., acrylic, epoxy, phenolic) types. In this section, we will briefly review several organic synthetic adhesives. Inorganic adhesives (cement, silicate, solder, etc.) will not be addressed herein.

Epoxy adhesives: These (thermoset) adhesives normally have two parts: the epoxy resin and its hardener. They are commonly used on large aluminum objects. Single-part, temperature-hardened epoxy adhesives can also be found in use in the manufacturing industry

Acrylic adhesives: This class contains a variety of (thermoset) subspecies: anaerobic, cyanoacrylate, and toughened acrylics. Anaerobic adhesives are one-part, solventless pastes, which cure at room temperature in the absence of oxygen. The bond is brittle. Cyanoacrylate adhesives are also one-part adhesives that cure at room temperature ("crazy glue"). Toughened acrylic adhesives are two-part, quick-setting adhesives that cure at room temperature after the mixing of the resin and the initiator. Overall, acrylic adhesives have a wide range of applications: metals in cars and aircraft, fiberglass panels in boats, electronic components on printed circuit boards, etc.

Hot-melt adhesives: These (thermoplastic) single-part materials include polymers such as polyethylene, polyester, and polyamides. They are applied as (molten) liquid adhesives and allowed to cure under (accelerated) cooling conditions. Owing to their modest strengths, they are not widely used for load-carrying applications.

The methods of applying adhesives onto prepared surfaces vary from industry to industry and are based on the type of adhesive materials: manual brushing or rolling (similar to painting), silk screening (placement of a metal screen on designated surfaces and deposition through cutouts on the screen), direct deposition or spraying using robot-operated pressure guns, and slot coating (deposition through a slot onto a moving substrate—"curtain coating").

10.2.3 Industrial Applications

Industrial examples of adhesive bonding include the following.

Automotive industry: Sealants and adhesives are widely used in the manufacturing of automobiles in temporary or permanent roles. On the welding line, examples include front hoods and trunk lids, hemming parts of door bottoms, front and rear fenders, and roof rails. On the trim line, examples include door trims, windshields, windows, wheel housings, and weather strips. Other automotive examples include (neoprene and nitrile rubber) phenolic adhesives used in the bonding of brake linings to withstand intermittent high shear loads at high temperatures, drain holes on body panels, and of course carpet fixing.

Machine-tool industry: Retaining adhesives have been utilized by machine-tool builders for strengthening a variety of bushings and bearings that are press-fitted against loosening due to intense vibrations (e.g., in chucks with hydraulic clamping mechanisms and in the spindle). Adhesives are also commonly used on a variety of body panels.

Other industries: Epoxy phenolics have been used in (aluminum-to-aluminum) bonding of honeycomb aircraft and missile parts onto their respective skins, in solar cells in satellites, and even in resin–glass laminates in appliances. One- or two-part epoxy adhesives have also been used in joining cabinet, telephone booth, and light fixture parts. Other examples include small electric armatures, solar heating panels, skis, tennis rackets, golf clubs, beverage containers, medical skin pads, loudspeakers, shoes, and glassware.

10.3 WELDING

Welding is a joining operation in which two or more segments of a product are permanently bonded along a continuous trajectory or at a collection of points through the application of heat. In certain cases, pressure can be utilized to augment the thermal energy expended. Most solid materials (metals, plastics, and ceramics) can be welded, though, with different difficulty levels.

The existing tens of different welding techniques can be grouped into two major classes: fusion welding and solid-state welding. The former class uses heat to create a molten pool at the intended joint location and may utilize a filler material to augment the existing molten pool for larger gaps, stronger bonds, difficult joint geometries, etc. The latter class utilizes heat and/or pressure for the welding process, though when heat is utilized the temperature is kept below the melting point of the segments to be joined.

In this section, our focus will be on fusion welding. Solid-state welding operations, such as friction welding and ultrasonic welding, will not be addressed herein. Also, joining operations involving brazing and soldering (often discussed with welding) will be addressed separately in Sec. 10.4.

Although welding became a widely used joining process after the introduction of electrical power in the mid-1880s, its origins can be traced to Egypt (1300s B.C.) and Rhodes (300s B.C.). These were rudimentary forge-welding processes using pressure and heat. The first (fusion-based) arc and resistance welding processes were commercialized during the period of 1880 to 1890 in England and the U.S.A. The use of oxyacetylene torches in arc welding, which utilize oxygen and acetylene for achieving a high-temperature flame, can be traced back to the period of 1900 to 1905. Today's most popular welding processes, however, were only developed during the period 1940–1960: gas tungsten arc welding (GTAW) in the late 1940s, gas metal arc welding (GMAW) in the mid-1950s, plasma welding in the late 1950s, and laser welding in the early 1970s.

As will be discussed below, welding is a complex manufacturing operation in which many process variables (such as feed rate and electrode angle) must be carefully controlled during the joining of two parts. The welding environment is quite hostile to humans owing to process temperatures, light emissions, and gases utilized. Thus in the past three decades two important trends have emerged: extensive use of robotic welders and widespread utilization of laser welding. Today, industrial robots have almost completely replaced human welders on manufacturing shop floors owing to their resistance to hostile environments and their capability of yielding repetitive high-quality welds.

10.3.1 Arc Welding

The most common fusion welding process, arc welding, involves the use of electric arc for the generation of extreme temperatures at a localized point (up to 10,000 to 20,000°C) in the joining of conductive metal workpieces. The electric arc is generated as (AC or DC) current passes between the welding electrode and the metal workpiece separated by a controlled short distance (Fig. 7). The welding electrode can be a consumable one, which itself acts as a filler material, or a nonconsumable one, which acts only as an arc generator and melter of an externally supplied filler material (normally in the form of a continuous wire). The extreme heat generated serves two complementary purposes: melting the regions of both workpieces at the closest vicinity of the joint and melting the filler material, thus forming a mixed continuous molten pool, which when solid forms a very strong bond. The primary contributors to the transfer of molten filler material (mostly as

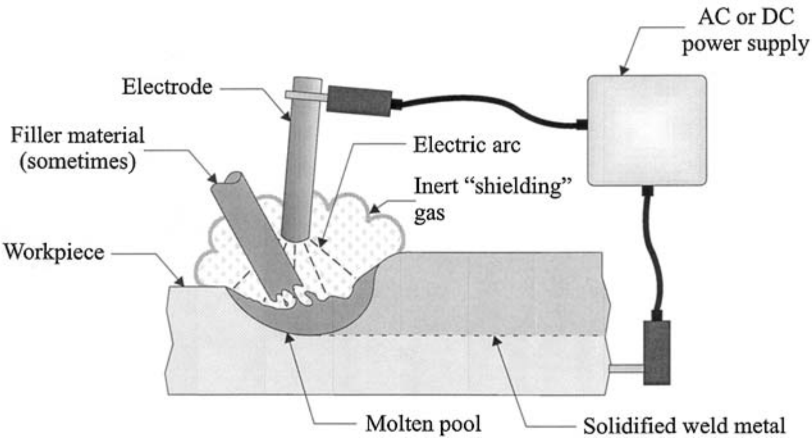


FIGURE 7 Arc welding.

drops or globules) into the welding zone include gravity, electromagnetism, and surface tension.

Since at high temperatures metals are very reactive to oxygen, hydrogen, and nitrogen present in the surrounding air, the welding region must be protected against such reactions through the use of inert gases such as argon and helium.

Weld Joints

The most common joints in arc welding are shown in Fig. 8. (a) Butt joints are connections between two sheets or plates; the weld penetrates through the parts' thickness. It is advised to configure the edges of both parts appropriately for a good flow of molten metal. (b) Corner joints are connections between two edges (30° to 150° relative inclination). (c) T-joints are orthogonal connections between two workpieces. (d) Lap joints are the fillet welding of two overlapping surfaces along one of the edges.

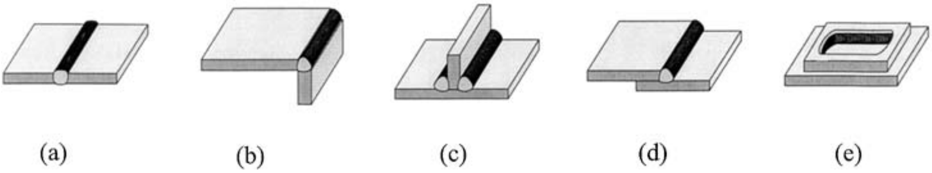


FIGURE 8 (a) Butt; (b) corner; (c) T; (d) lap; (e) slot weld joints.

These joints are commonly used for thin-sheet products. (e) Slot joints are connections between two parts through the fillet welding of the inner edge of the slot (periphery welding).

Shielded Metal Arc Welding

Shielded metal arc welding (SMAW) is primarily a manual process; a consumable electrode is advanced in the direction of the desired joint trajectory while being fed into the welding region according to the rate of consumption. The electrode is the metal filler melted into the joint (Fig. 9). This electrode is coated with a material that melts concurrently with the "stick," providing the weld region with necessary protective gas against reaction with the surrounding air. The power source can be either AC or DC. The electrical current is in the range of 150 amps (for AC) to 400 amps (for DC) at voltage levels of 15 to 45 volts. The diameter of the rod/stick (1.5 to 10 mm) dictates the current level—thinner rods require less current. Naturally, these rods have to be repeatedly replenished, making SMAW a process that is difficult to automate.

Gas Metal Arc Welding

In gas (shielded) metal arc welding (GMAW), also known as metal inert gas (MIG) welding, a protective region is established around the weld pool through a continuous supply of inert gas. The consumable (bare) wire is fed

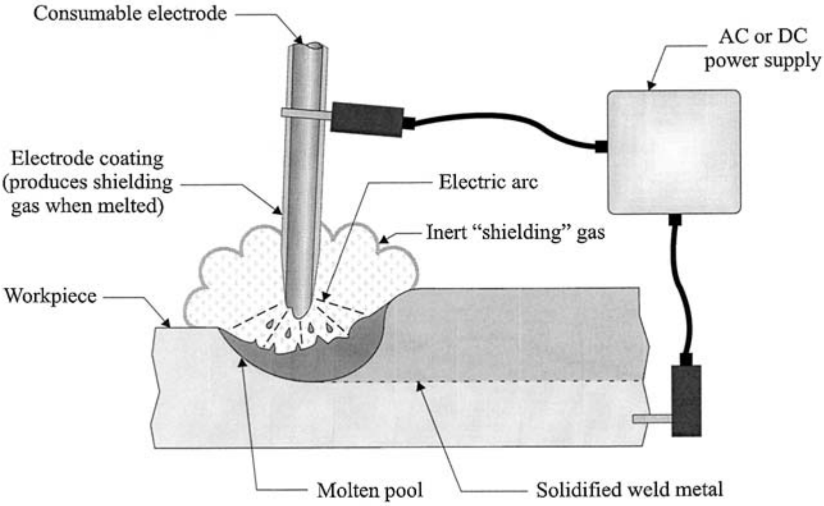


FIGURE 9 Shielded metal arc welding.

into the weld pool through a wire guide within a nozzle that supplies the shielding gas as well (Fig. 10). GMAW can be utilized for the welding of different metals, at high speeds (up to 10 m/min) and with minimum distortion. Owing to its continuous wire-feed feature (supplied in reels), GMAW is suitable for robotic applications.

The selection of filler wires, in diameters of 0.6 to 6.4 mm, depends on the material of the two parent workpiece segments. Frequently, steel wires are coated with copper for better conductivity, reduction of feeding friction, and minimization of corrosion while kept in stock. The selection of inert shielding gas also depends on the welding material: argon (Ar) is very suitable for nonferrous metals and alloys; additions of 12% oxygen into argon yields higher arc temperatures and increases wetting—this mixture is suitable for stainless steel welding; mixtures of argon and helium are suitable for aluminum, magnesium, nickel and their alloys; and high-purity argon

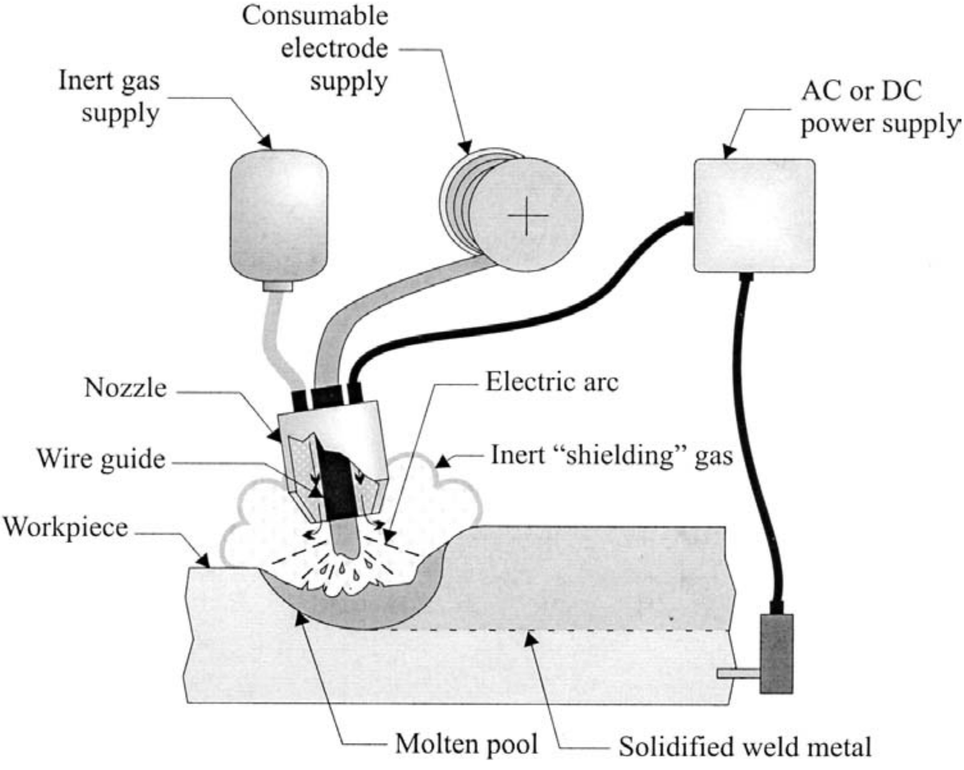


FIGURE 10 Gas metal arc welding.

gas is necessary for highly reactive metals such as titanium, zirconium, and their alloys.

Numerous operating parameters must be controlled when welding with a shielding inert gas: welding current influences the deposition speed and the shape of the weld—increased current increases the size of the weld pool and penetration, while the width of the bead remains practically unchanged; arc voltage also influences deposition—increased arc voltage yields enlarged bead width, while having diminished penetration; welding speed directly influences the quality of the weld joint—excessive speed yields nonuniform welds, while slow speed prevents deeper penetration. One must carry out extensive experimentation for combinations of different materials and shielding gases in order to obtain the optimal values for the three important process parameters: welding speed, arc voltage, and welding current.

Gas Tungsten Arc Welding

Gas tungsten arc welding (GTAW), also known as tungsten inert gas (TIG) welding, utilizes a nonconsumable electrode for the generation of very high welding temperatures. Since the filler wire no longer constitutes an electrode that has to be kept at a distance from the workpiece, it can be fed directly into the weld pool with no spatter to yield high quality weld joints (Fig. 11). Although targeted mostly for nonferrous metals, GTAW can be utilized for the welding of all metals, even for the joining of

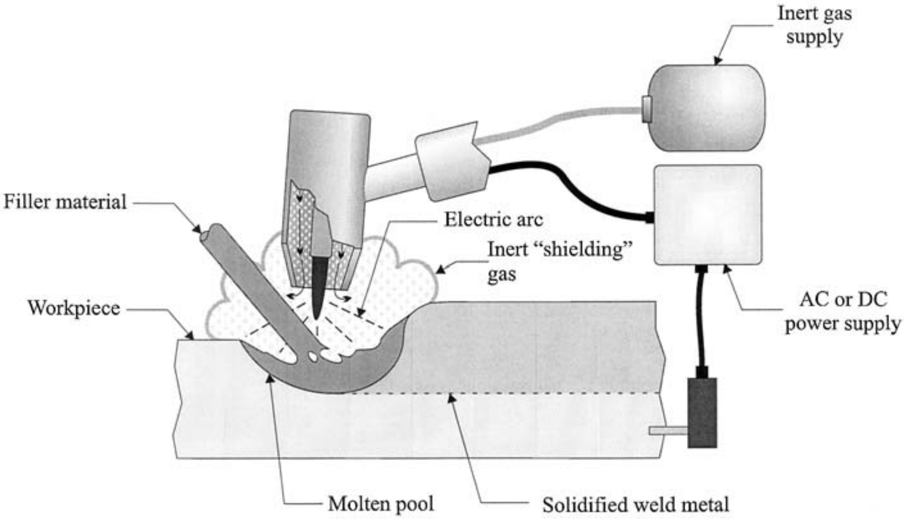


FIGURE 11 Gas tungsten arc welding.

dissimilar metal segments. Argon is utilized for the welding of most metals, with the exception of some alloys of aluminum and copper, for which helium is the recommended shielding gas. Mixtures of argon and helium are also commonly used in high-speed GTAW—the addition of helium improves penetration.

Tungsten electrodes range in diameter (1 to 8 mm) and allow welding currents of up to 800 amps. However, owing to very high electrode temperatures, the welding torch is equipped with a ceramic nozzle to hold the tungsten electrode and a water-based cooling system. Occasionally the tungsten electrodes may have to be ground for the welding of thin materials.

10.3.2 Spot Welding

In resistance spot welding, joining is achieved through a localized heating effect occurring due to an electrical current encountering resistance during its flow. When a large current (up to 100,000 amps) at a low voltage (up to 10 volts) is passed through two very highly conductive electrodes in contact with a pair of lower-conducting plates, heat is generated between the two plates along the line of the current, causing local melting. The localized welding of the two materials is normally augmented by applying pressure also directly along this line of current (Fig. 12).

Spot welding of thin-walled plates (less than 3 to 5 mm) using welding guns is the predominant joining operation in car bodies (up to 1,500 to 3,000 joints per vehicle), typically performed by industrial robots. Although such welds are extremely strong, one must always carefully control the welding cycle: the actual weld time, when current is

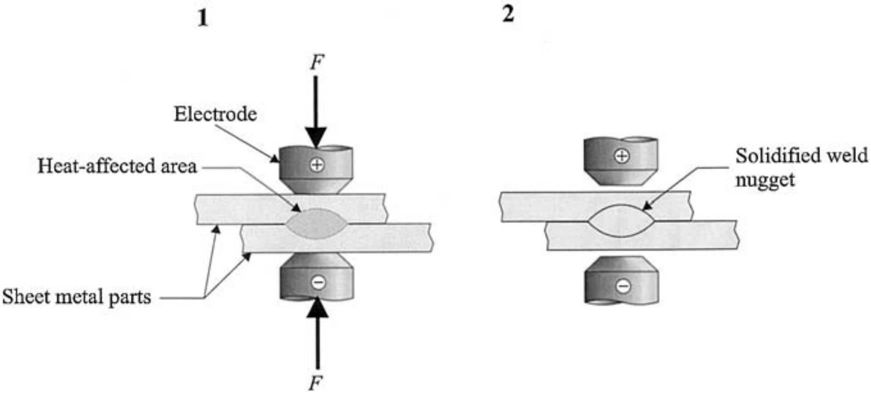


FIGURE 12 Spot welding.

applied under constant pressure, and the cooling period, when the current is off but the pressure is maintained for a little while more. Also, the electrodes (with water-cooling systems) should have the following properties: high electrical conductivity, high thermal conductivity, high resistance to mechanical deformation, and low adhesiveness to metals being welded.

10.3.3 Laser-Beam Welding

Laser-beam welding is a thermal process that utilizes a high-energy coherent light beam to melt particles on the surfaces of two adjacent workpieces for their permanent joining. As first discussed in regard to laser-beam machining in Sec. 9.2, the term laser is an acronym—light amplification by stimulated emission of radiation. A laser source converts electrical energy into a high-energy light beam, which is subsequently converted into heat as it is absorbed by the recipient material. In laser beam welding, this heat generation leads to the formation of a liquid melt pool. As the laser spot travels along a trajectory (i.e., continuous welding), the liquid pool advances forward, while the past location of the spot solidifies and forms a permanent joint between the two parts.

Laser welding offers several unique advantages over other traditional welding processes: it can produce a high-intensity spot at remote, difficult-to-reach locations (or even along continuous trajectories); it yields minimal distortions and high-quality uniform joints; it facilitates the welding of dissimilar materials without the use of filler materials; and it allows high welding speeds. As in laser beam machining, however, laser beam welding may be more challenging for highly reflective material, such as aluminum and copper.

Lasers

The three primary classes of lasers are gas, liquid, and solid. All lasers operate in one of the two temporal modes: continuous wave and pulse. The two most commonly used lasers in welding are as follows.

Nd:YAG: The neodymium-doped yttrium aluminum garnet ($Y_3Al_5O_{12}$) laser is a solid-state laser. Although very low in efficiency, its compact configuration, ease of maintenance, and ability to deliver light through a fiber-optic cable makes it an excellent choice for welding. In pulsed mode, a Nd:YAG laser can deliver an output power of up to 50 kW at a frequency of up to 500 Hz.

CO_2: The carbon-dioxide laser is a gas laser that can deliver an output power of up to 25 kW in continuous wave mode. It is the most efficient commercial laser (up to 10%)—though still a very inefficient power

source, when efficiency is measured as the ratio of output power to input power. CO_2 lasers, however, cannot be coupled to fiber-optic systems.

Continuous Welding

Most of the joint configurations shown in Fig. 8 for continuous arc welding can be achieved using laser beam welding, commonly with CO_2 lasers. As in laser beam machining, the laser spot can be focused onto the surface region of the weld joint using moving optics systems for faster welding speeds or by utilizing a moving workpiece system. In all cases, however, a shielding gas must be supplied to the welding region (Fig. 13).

Spot Welding

Spot welding was the first attempt in joining metals via a laser light source. Today, (lap joint–type) spot welds can be achieved by using both Nd:YAG and CO_2 lasers by creating a localized melting point between two parts in contact. Nd:YAG lasers are suitable for spot welding due to the very high intensity heat impulses they can generate at high frequencies. Such pulsed mode lasers have also been used in the welding of small-diameter wires or very thin walled sheets of metal—"microwelding."

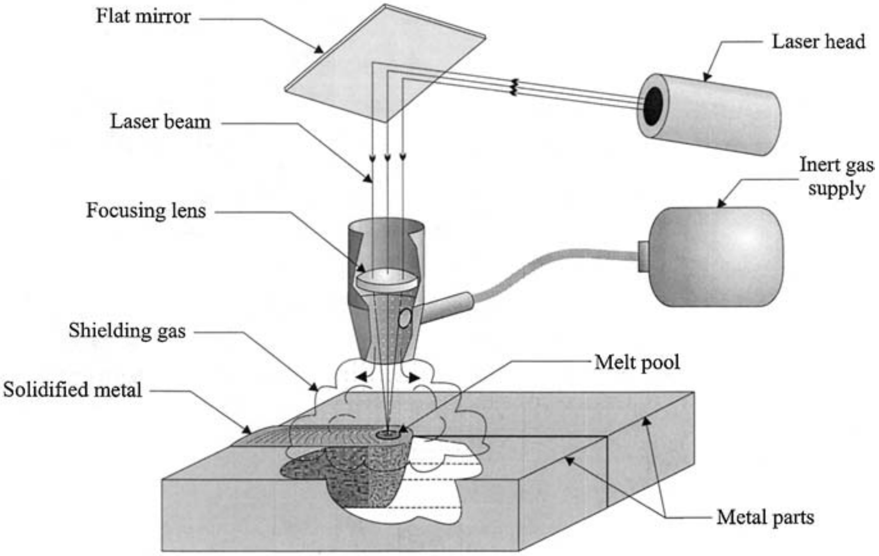


FIGURE 13 Laser welding.

Applications

Probably the best known application of laser welding is the spot welding of the two blades on the Gillette Sensor Razor (a total of 13 welds). The fabrication line for this product utilized thirty Nd:YAG lasers with fiber-optic light-delivery systems yielding a production rate of three million welds per hour. Other less known examples of laser welding include gears, steering units, engine parts and body parts for the automotive industry, TV picture tubes, food mixer parts and pen cartridges for the consumer goods industry, and heat-exchanger tubes for the nuclear industry.

10.3.4 Weldability and Design for Welding

Most engineering materials (metals, plastics, and ceramics) can be welded—some with more difficulty than others, using one of the available welding techniques. Due to the melting and solidification cycle and the resultant microstructure changes, one must carefully monitor all the welding process parameters, including shielding gases, fluxes, welding current and voltage, welding speed and orientation, and preheating and cooling rates.

In terms of different materials: carbon and low-carbon alloy steels are weldable with no significant difficulties—thicknesses of up to 15 mm are more easily weldable than thicker workpieces that require preheating (to slow down the cooling rate); aluminum and copper alloys are difficult to weld because of their high thermal conductivity and high thermal expansion; titanium and tantalum alloys are weldable with careful shielding of the weld region; thermoplastics (such as polyvinychloride, polyethylene, and polypropylene) are weldable at low temperatures (300 to 400°C), though glass-reinforced plastics are not generally weldable; ceramics (SiO_2-AlO_2) have also been welded in the past using CO_2 and Nd:YAG lasers with some preheating.

Welding defects can be classified as external (visible) and internal defects. Some of these are listed below (Fig. 14):

Misalignment: It is an external defect caused by poor preparation.

Distortion: It is an external defect caused by residual stresses due to unsuitable process parameters.

Incomplete penetration: It is an internal defect caused by excessive weld speed, low weld current, too small a gap, or poor preparation.

Undercut: It is an internal defect—a groove that appears at the edge of the joint, caused by high current or voltage, irregular wire speed, or too high welding speed.

Porosity: It is an internal defect—in the form of isolated or grouped bubbles, caused by an insufficient flow of gas, moist or rusty base metals, or entrapment of gases.

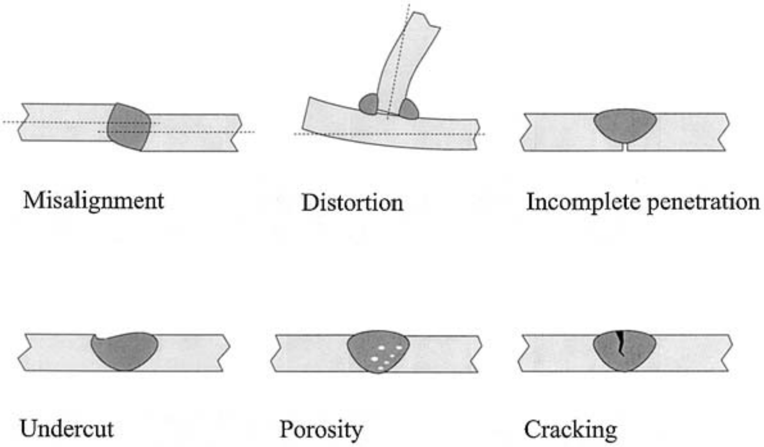


FIGURE 14 Welding defects.

Cracking: It is an internal defect—localized fine breaks that may occur while the joint is hot or cold, caused by hydrogen embrittlement, internal stress, lack of penetration, excessive sulphur and phosphorus content in base metal, or rapid cooling.

In addition to the process parameters that must be controlled to avoid welding defects, a designer may consider the following additional guidelines: weld locations should be chosen to maximize strength and avoid stress concentrations, though some awareness of intended use and appearance is important; careful edge preparation must be employed if unavoidable; and welding should be minimized owing to potential dimensional distortions.

10.4 BRAZING AND SOLDERING

Brazing and soldering are similar joining processes: a filler metal is melted and deposited into a gap between segments of a product. Unlike in welding, the base materials (similar or dissimilar) are not melted as part of the joining process. In brazing, the filler material normally has a melting point above 450°C (840°F), but certainly lower than that of the base materials, whereas, in soldering, the filler materials have melting points well below 450°C. Capillary forces play an important role in both processes in the wetting of the joint surfaces by the molten (fluid-state) filler material and thus the flow of the liquid metal into the gaps between the two base segments.

The use of low-melting-point metals in joining operations has been around for the past 3,000 years. The primary advantages of such processes have been joining of dissimilar materials joining of thinned walled and/or complex geometry parts that may be affected by high temperatures (such as those in welding), achievement of strong bonds (stronger than adhesive bonding but weaker than welding), and adaptability to mass production and automation.

In the following two subsections, the fundamental issues in brazing and soldering will be presented.

10.4.1 Brazing

Brazing is a simple joining process, in which a liquid metal flows into narrow gaps between two parts and solidifies to form a strong, permanent bond. Ferrous and nonferrous filler metals normally have melting temperatures above 450°C, but below those of the two base materials, which do not melt during the joining process. Almost all metals, and some ceramic alloys, can be brazed using filler metals, such as aluminum and silicon, copper and its alloys, gold and silver and their alloys, and magnesium and nickel alloys.

The ability of the liquid filler metal to wet the materials it is attempting to join, and completely to flow into the desired gaps prior to its solidification, determines the success or failure of a brazing application. The most commonly utilized wetting metric is the contact angle (Fig. 15a). In 1805, T. Young concluded that for each combination of a solid and a fluid there exists a corresponding contact angle that is governed by the following (Young's) surface tension angle,

$$\gamma_S = \gamma_L \cos\theta + \gamma_{SL} \tag{10.1}$$

where γ is the surface tension (J/m), the subscripts S and L refer to solid and liquid surfaces, respectively, and SL refers to the solid–liquid interface. Acceptable wetting occurs when the contact angle is less than 90° (Figs. 15b and 15c).

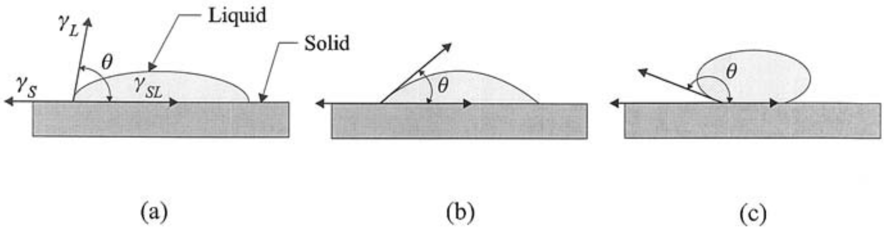


FIGURE 15 (a) Contact angle θ; (b) $\theta < 90°$, wetting; (c) $\theta > 90°$, no-wetting.

Besides surface tension, the following parameters affect the brazing process: temperature and duration of melting, surface preparation, joint design and gap dimensions, source and rate of heating, and, naturally, base material and filler metal characteristics.

In the past three decades, the brazing process has been successfully automated and applied in numerous industries. Several such examples are listed:

Cemented carbides onto cutting tools' metal shanks.
Ceramic (automotive) bladed–turbocharger hubs onto metal shafts.
Ceramic-on-metal joining in microelectronic products.
Metal-on-metal (automotive) pipes.

Joint Design in Brazing

The brazing metal filler is normally applied to a preheated joint through the melting and deposition of a rod or a wire. However, commonly, the brazing metal can be placed in the immediate vicinity of the joint prior to heating, in the form of preformed rings, disks, slugs, etc. Subsequent capillary forces that develop during heating draw the molten filler metal into the intended clearances (Fig. 16). Bond integrity and strength depend on joint geometry, clearances, and surface cleanliness.

Butt and lap joints are the two primary brazing joint configurations (Fig. 17). Butt joints are simple in design and preparation. However, in such joints, all of the load is transmitted in the undesirable tensile stress form, where the thinnest section of the joint dictates the strength of the joint. Lap joints' strengths do not depend on the cross sections of the components, and the load is normally transmitted in the desirable shear stress form. In both configurations, however, the clearance must be carefully controlled—beyond an optimal gap, the capillary forces may not be enough to uniformly distribute the filler metal fluid through the joint. Although joint clearances are functions of the filler and base materials, the empirical, ideal gap has been traditionally defined as 0.05 to 0.15 mm (up to 0.25 mm for precious metals).

Materials and Environment in Brazing

The brazing of all metals and ceramics depends on the wetting of the filler material at relatively high temperatures. Formation of unwanted oxides at such high temperatures, however, may impede the ability of the filler material to wet the joint surfaces. Use of a suitable flux complemented with an inert gas atmosphere dissolves and/or prevents the formation of oxides and promotes wetting by lowering the surface tension of the filler

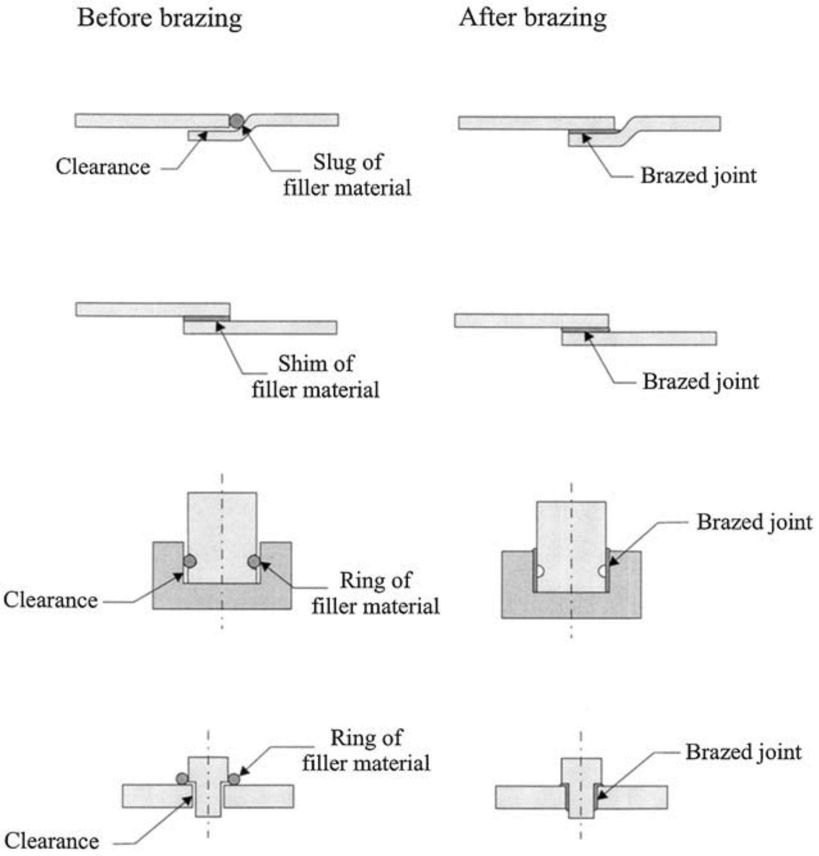


FIGURE 16 Preapplication of filler metal.

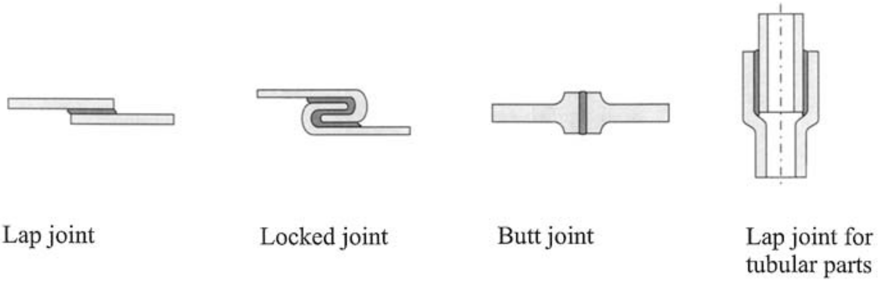
metal. Common fluxes used for brazing include chlorides, fluorides, borates, and alkalis.

Filler materials commonly used in brazing are

Aluminum–silicon: This group of alloys can be used as fillers for aluminum (and its alloys) base materials at melting temperatures of 500°–600°C—heat exchangers, aircraft parts, car radiators, etc.

Copper and copper–zinc: This group of alloys can be used as fillers for ferrous-base materials at melting temperatures of 750 to 1700°C.

Nickel and nickel alloys: This group of alloys can be used as fillers for stainless steel, nickel, and cobalt-based alloys at melting temperatures of 950 to 1200°C.


Lap joint

Locked joint

Butt joint

Lap joint for tubular parts

FIGURE 17 Brazing-joint configurations.

Silver-copper: This group of alloys can be used as fillers for titanium, ceramics, steel, and nickel at melting temperatures of 620 to 850°C—honeycomb structures, tubing, etc.

Brazing Methods

Manual torch brazing is the simplest and most commonly used technique, primarily reserved for one-of-a-kind (repair or prototyping) jobs. Other brazing techniques that allow automation for batch or continuous processing include

Furnace brazing: Parts with preplaced filler segments are brazed in (electric, gas, or oil-heated) furnaces that typically employ a conveyor for (time-controlled) continuous through motion of the parts to be joined.

Induction and resistance brazing: Electrical resistance is utilized to melt preplaced filler materials quickly.

Dip brazing: Complete immersion of small parts into a (constant-temperature) molten filler material vat provides wetting and filling of the joints.

10.4.2 Soldering

Soldering is a joining process in which two segments of a product are bonded using a liquid filler material (solder) that rapidly solidifies after deposition. As in brazing, the process occurs at the melting temperature of the solder (typically, below 315°C), which is significantly below the melting temperature of the base material. Wetting of the joint surfaces by the liquid solder and its flow into the desired gaps of optimal clearances due to capillary forces is a paramount issue in soldering. Due to wetting and bonding of the joints at low temperatures, soldering is a desirable joining process for applications with no significant load carrying situations, such as soldering of electronic components on printed circuit boards (PCBs).

Joint design guidelines for soldering are very similar to those established for brazing. Of the two most common joint configurations, butt and lap joints, the lap joint is the preferred one because of its strength (Fig. 18). Since joint strength is directly related to overlap area, designers must carefully configure lap joints for achieving uniform solder flow into the gaps. A common solution to such flow problems, however, is the preplacement of the solder prior to heating. Preplacement can be achieved using solid preforms of solders, such as washers, wire rings, discs, or powder form solder suspended in a paste.

The soldering process starts with a careful preparation of the surface—removal of contaminants and degreasing. An appropriate soldering flux is then applied to prevent oxidization and facilitate wetting. Inorganic fluxes include hydrochloric and hydrofluoric acids and zinc chloride and ammonium chloride salts. Organic fluxes include lactic and oleic acids, aniline hydrochloride halogens, and a variety of resins. Fluxing is followed by the joining process, where molten solder is directly applied to the joint area or heating is applied to melt the preplaced solder. Once the joint is cooled, all flux and solder residues must be removed.

Soldering Materials

For successful soldering, the base metal, the solder, and the flux materials must be chosen concurrently. Although most metals can be soldered, some are easier to solder than others: copper and copper alloys are the easiest base metals to solder, so are nickel and nickel alloys, while aluminum and its alloys, titanium, beryllium, and chromium are not normally soldered. The primary reason for our inability to solder materials in the last group is the difficulty encountered in removing the oxide film (i.e., fluxing) at the low temperatures of soldering.

Most commonly used solders are tin–lead alloys, with occasional addition of antimony (less than 2 to 3%). The equilibrium diagram of the

FIGURE 18 Soldering lap joint configurations.

tin–lead alloy is shown in Fig. 19. As can be noted, the eutectic composition of this alloy comprises approximately 62% tin and 38% lead, with a discrete melting point of 183°C. (The word eutectic derives from the Greek word *eutectos* meaning easily meltable.) On both sides of this composition, the alloys go through a transition phase (in "pasty" form) when being converted from solid to liquid.

Since tin is an expensive material, manufacturers may choose to use lower percentages of tin in the tin–lead alloy, at the expense of higher melting points. The electronic industry prefers to use the eutectic composition due to its rapid solidification at the lowest melting point level. Other solder materials include tin, silver, tin–zinc, tin–bismuth, and cadmium–silver. Tin–silver, for example, would be used for applications (intended product usages) with high service temperatures, since they have higher melting points (221°C) than do most tin–lead solders (183°C).

Soldering Methods

Soldering is a highly automated method of joining metal components. Most soldering methods can be classified according to the application of heat: conduction (e.g., wave soldering), convection (e.g., reflow soldering) and radiation (e.g., infrared and laser beam soldering).

Wave soldering: In this automatic method, a pump located within a vat of solder (heated through conduction) creates an upward spout (a laminar

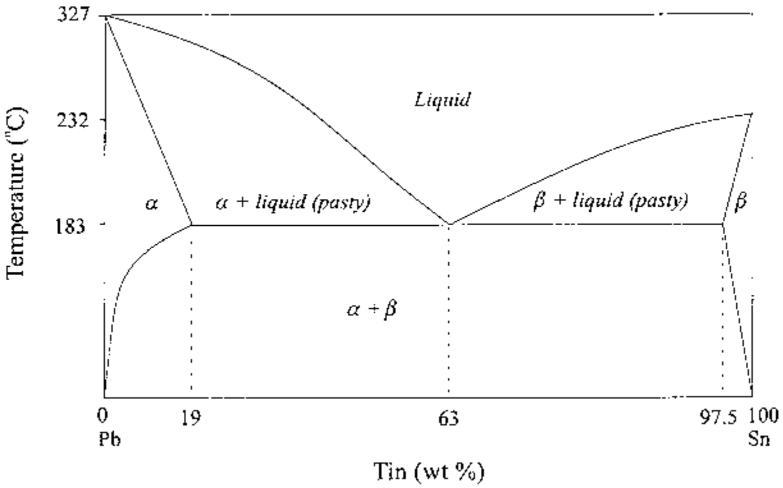


FIGURE 19 Equilibrium diagram for tin–lead alloy.

flow wave). Exposed metal joints are passed over this wave in a continuous motion, where liquid solder attaches itself to the joint due to capillary forces (Fig. 20). Wave soldering is one of the most common techniques used in the electronics industry, especially, for the joining of through hole components.

Reflow soldering: Remelting of preplaced/predeposited solder between two surfaces, for forming the intended joint, using a convection-type heat source is normally called reflowing. In the electronics industry, reflowing is commonly utilized for the soldering (via wetting of predeposited solder paste) of surface-mount devices on PCBs. (Occasionally, the term reflow soldering is erroneously utilized for soldering in infrared ovens).

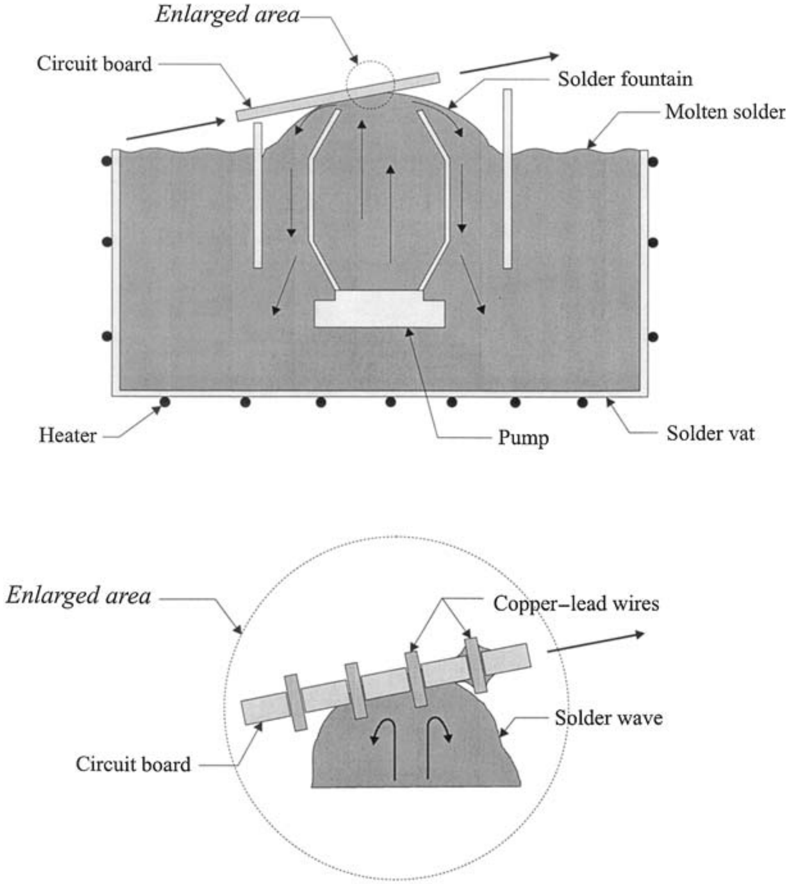


FIGURE 20 Wave soldering in electronics industry.

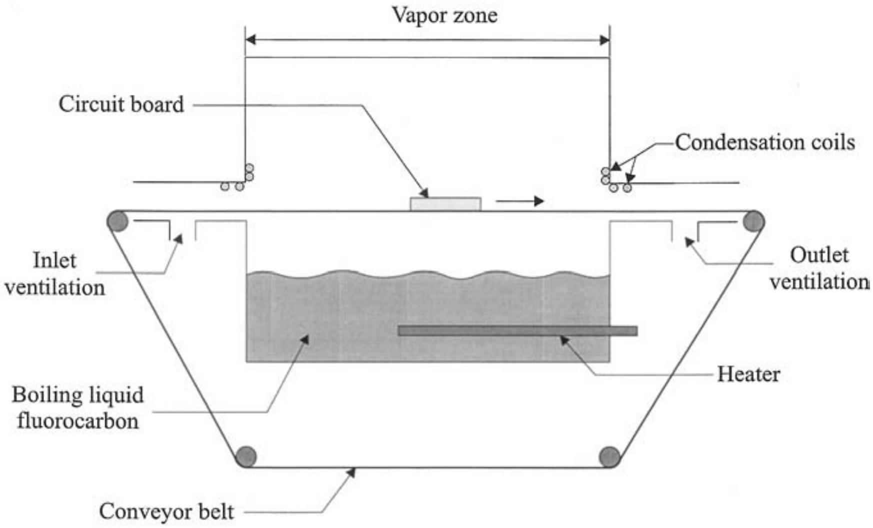


Figure 21 Vapor-phase soldering.

Infrared reflow soldering: In infrared ovens, remelting of preplaced solder is achieved via electromagnetic radiation in the far range of the 0.75 to 1000 μm infrared wavelength. As one would expect, however, only 20 to 30% of heat in such ovens is provided by radiation. Convection provides the remaining percentage of heat, thus eliminating potential shadowing problems. Some infrared ovens also utilize inert gas atmospheres.

Vapor phase soldering: This convection based heat transfer method (developed in 1973 by Western Electric Company, U.S.A.) provides soldering ovens with excellent temperature control and uniformity of heating. A liquid vat (normally with fluorinated hydrocarbon fluid) is utilized to generate vapor with good oxidation resistance and fill a chamber, through which a product (usually PCBs) with preplaced solder moves.

The vapor, when in contact with the product, raises the temperature of the solder to the boiling temperature of the liquid in the vat and allows it to reflow and form the necessary joints (Fig. 21). As the joints are formed, the product is retrieved from the oven for fast solidification.

10.5 ELECTRONICS ASSEMBLY

The use of electronic products during the period 1950–1980 was primarily restricted to industrial purposes, such as control of manufacturing machines, aircrafts, and large-scale computers. The computer revolution that started in the early 1970s brought electronic products into many households, such as hand-held calculators, telephones and answering machines, microwave ovens, and eventually personal computers. Today, most modern household appliances and automobiles have extensive numbers of electronic components in them. (This trend eventually led to the development of a new engineering field, mechatronics, broadly defined as the use of electronic components in the operation and control of mechanical systems.)

The manufacturing of an electronic product starts with the fabrication of its individual components, such as resistors, capacitors, and integrated circuits (ICs). The production of an IC, in turn, starts with the production of a single-crystal silicon ingot (up to 150 mm diameter and sometimes more than 1 m long solid cylinder), which is subsequently sliced into thin disc-shaped wafers (approximately 0.5 mm in thickness).

Through traditional processes such as lithography and etching (Chap. 9), thousands of ICs can be built on a single wafer and then separated for individual (or group) packaging. Packaging refers to the preparation of these devices for future connection onto PCBs, for example, attachment of heads and encapsulation in ceramic carriers. Two common technologies for component attachment onto a PCB (i.e., electronics assembly) are through-hole mounting, also known as pin-in-hole (PIH), and surface-mount technology (SMT).

10.5.1 Component-to-Board Connections

PCBs, also known as printed-wiring boards (PWBs), have the following primary functions: to provide a mounting surface for most of the components and allow component-to-component connections through a (printed) wiring system. Most PCBs are laminates of one or more layers of copper claddings (copper foils) separated by dielectric laminates (most commonly, polymers reinforced with glass cloth, cotton fabric, paper, etc.) (Fig. 22).

Lithography and etching are the primary processes used in the fabrication of a desired connection configuration on a copper foil (attached

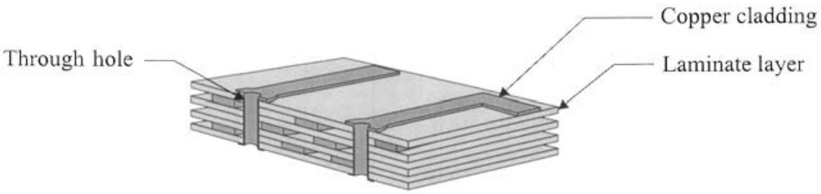


FIGURE 22 Printed-circuit-board configuration.

to an underlying dielectric laminate). Holes on PCBs (for interlayer connections and PIH component attachments) are normally punched or drilled. The design of the connection configurations and the spacing of components must be carefully considered in the fabrication of optimal size PCBs, which should also allow efficient assembly of components (also known as the "population" of a board) and testing of functionality.

As mentioned above, two common technologies used in component-to-PCB connections are through-hole and surface-mount technologies. In PIH connections, a connection is established by soldering the leads (pins) of the components onto the PCB by depositing molten solder at the holes and allowing it to wet the complete region due to capillary forces and solidify (Fig. 23a). In SMT, the components are placed on holeless PCB regions configured with landing areas for electrical connections to the components. These "lands" have already been equipped with predeposited solder paste prior to the placement of the components. Some SMT-connection (joint) configurations are shown in Fig. 23b.

The two most common SMT (IC-package) connections have long been the gull-wing and the J leads (Fig. 23). However, owing to the intense pressure for miniaturization of components since the early 1990s, manufacturers developed a very effective connection technology, named ball-grid-array (BGA) packaging. The BGA technology was to provide the electronics industry with a capability for more than 1,000 I/O connections per device, though recent BGA devices provide less than half of this targeted number.

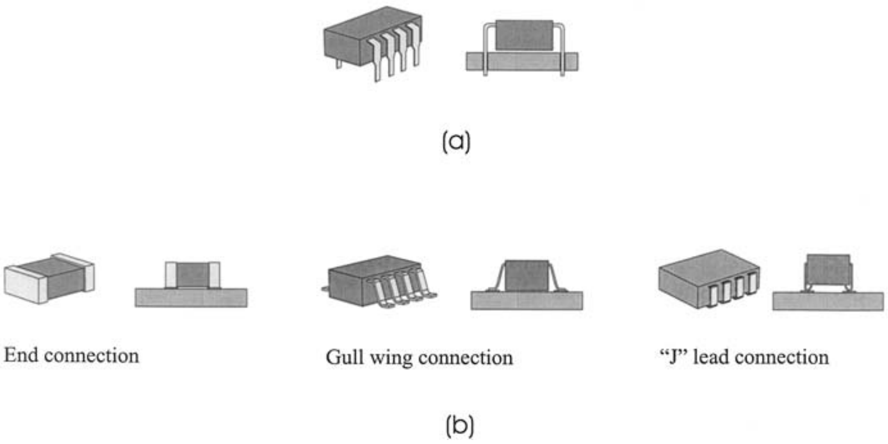


Figure 23 (a) Through-hole; (b) surface-mount connection.

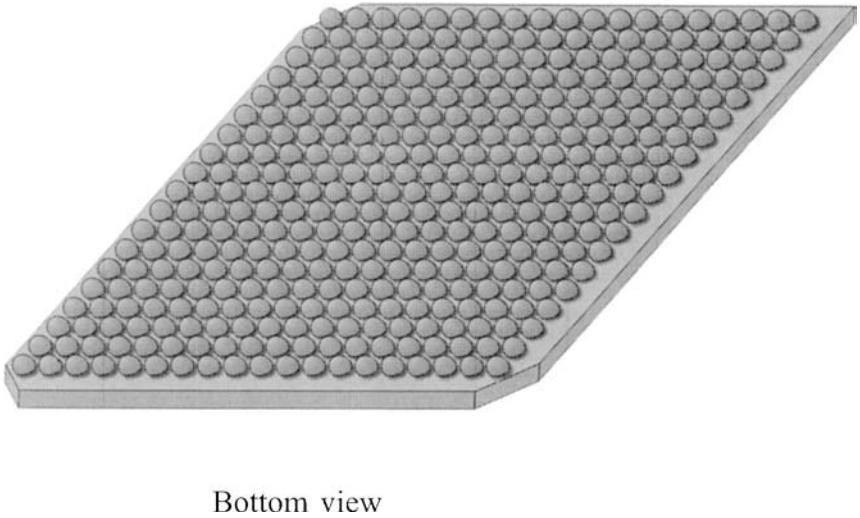


FIGURE 24 Ball-grid array I/O connections.

The contacts are normally less than 0.8 mm solder spheres attached to the bottom of the device in an array form (Fig. 24).

Beside their primary advantage of high I/O intensity, BGA devices also provide ruggedness and excellent thermal energy management. Their primary disadvantage is the severe difficulty of inspection, which may make them unattractive to small companies. BGA connections can only be inspected via computed tomography–type technologies that are capable of collecting x-ray- or ultrasound-based cross-sectional information about the flow of solder. This quality-control issue will be further addressed in Chap. 16 of this book.

A variation of BGA technology has been the utilization of cylindrical solder columns instead of spheres.

10.5.2 Assembly Process

In this section, our emphasis will be on the assembly process of SMT components, which differs from PIH component assembly, primarily on the placement subprocess of the individual components. SMT components rely on adhesives for remaining securely attached to the board prior to soldering, while the leads of PIH components must be slightly bent after insertion into their respective holes for secured attachment.

SMT technology was originally applied in military and aerospace industries in the mid-1960s for the major reason of yielding significantly higher densities than those offered by PIH technologies. These were ribbon-leaded flat packs comprising a ceramic package with flat ribbon leads (similar to today's gull-wing leads). The next generation SMT components, hermetic leadless chip carriers (HCC or LCC) became available in the early 1970s. However, these components faced compliancy (stress-relief) problems when placing ceramic components directly on organic (polymer-based) boards. The problem was overcome in the late 1970s with the introduction of plastic SMT packages. Today, SMT-based products can be found in all industries: automotive, aerospace, medical, and so on.

The typical assembly process of a two-sided PCB with SMT components is shown in Fig. 25. The primary steps in this process are solder paste application, adhesive application (if necessary), component placement, reflow soldering, solvent cleaning, and quality control.

Solder-paste application: Solder paste is, normally, a homogeneous, viscous material containing solder powder and flux material. Besides its primary function of joining the SMT components onto the PCB, it can also act as an adhesive that holds the component in place until soldering. The application of this paste onto the PCB can be achieved via screen (or stencil) printing, syringe dispensing, or pin transfer. Screen printing is the most widely utilized technique, where (in off-contact printing) the solder paste is flooded onto and forced through a screen onto the PCB (Fig. 26). The process is highly automatable.

Adhesive application: Syringe-dispensing or pin-transfer techniques can effectively apply adhesives to necessary points (dots) on the PCB.

Component placement: The pick-and-place operation of components refer to (normally vacuum-based) picking of a component from a feeder,

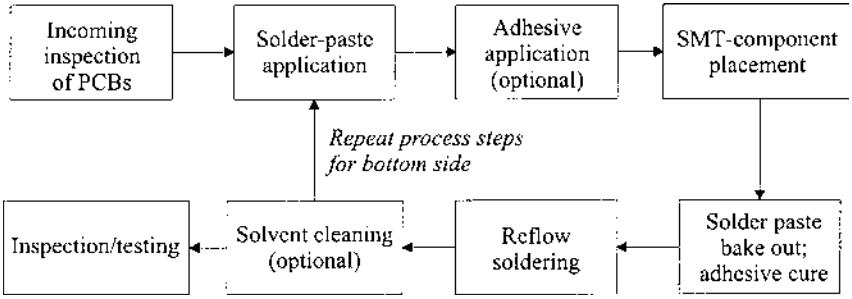


FIGURE 25 SMT assembly process.

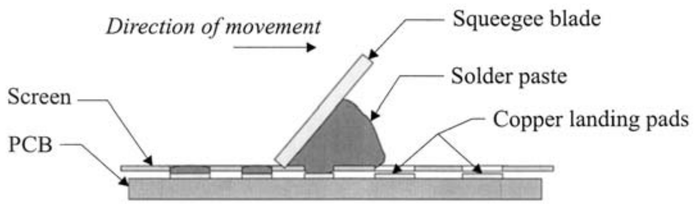


FIGURE 26 Screen printing of solder paste.

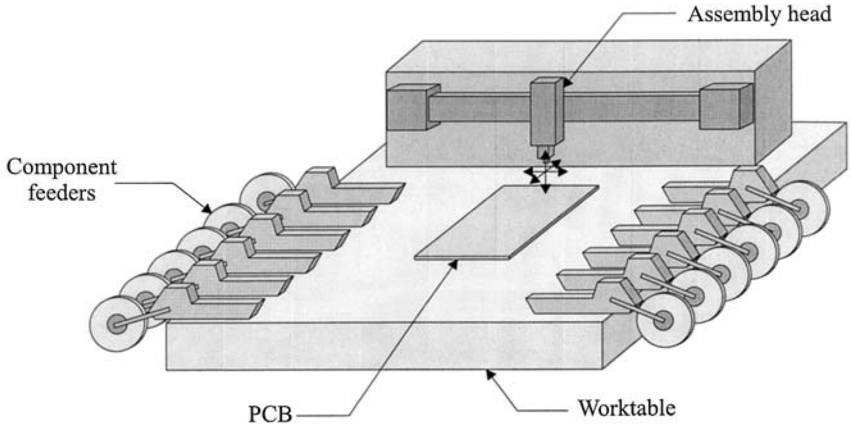
aligning it with its designated placement position and orientation, and releasing it. In sequential placement machines, this cycle is repeated for every component. Two variations of this machine are the fixed-PCB and moving-placement-head configuration versus moving-PCB and fixed- (but maybe rotating about the Z axis) placement-head configuration. Such gantry-type, X–Y planar, robotic placement machines can place up to 30,000 parts per hour, when placing components such as resistors and capacitors presented to the placement head on tapes and reels (Fig. 27). (Much lower rates would be achieved by special-purpose industrial robots utilized for the placement of irregular geometry components.)

Recent versions of placement machines include two placement heads working in concert for faster placement rates, especially for difficult-to-place components, which are fed using single-line magazines or array-type trays. Prior to z-axis motion placement of components with tight tolerances, most machines rely on position and orientation feedback of placement location achieved through a machine-vision system for minor adjustments in the x–y placement of the component.

Soldering: Prior to soldering, in most cases the populated board is subjected to sufficient heating for baking of the flux (solder) binder and the curing of the adhesives for better attachment, with an added side benefit of reducing potential gas escape during soldering. Most soldering equipment utilized in the electronics industry is of the conveyer type owing to mass production requirements. Reflow soldering using vapor-phase and infrared ovens is very common (Sec. 10.4). Wave soldering is applied to PIH components.

The above assembly process is concluded by a cleaning stage, prior to the inversion of the PCB for the assembly of components on the other side (for two-sided boards). The primary cleaning task is the removal of flux residues after the soldering process (especially critical for SMT components). If left on the board, such contaminants could lead to electrical and mechanical failures. Water-based washing is the most common cleaning technique.

Fixed PCB, moving placement head



Fixed placement head, moving PCB

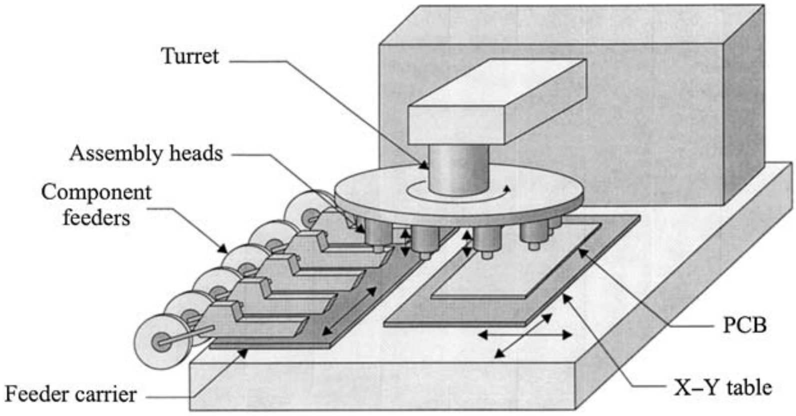


FIGURE 27 Component placement machines.

10.6 AUTOMATIC ASSEMBLY OF SMALL MECHANICAL COMPONENTS

The automatic assembly of small mechanical (versus electronic) components can be traced to the earlier part of the 20th century, though the widespread utilization of such nonprogrammable automation only started in the second half of the century, with the design and configuration of dedicated, single-purpose assembly machines. Then came the pioneering works of G. Boothroyd and P. Dewhurst, who challenged engineering designers to “think automation” when designing for assembly and to configure product geometries suitable for automatic assembly that does not rely on any sensory feedback. The majority of the literature on automatic assembly is in one way or another based on their work, and this section is no exception.

The primary joining operation relevant to automatic assembly discussed in this section is mechanical fastening, though parts positioned and oriented using the techniques described in the following subsections could be beneficial to other joining operations, such as adhesive bonding and soldering.

The first challenge in automatic assembly is the sorting and orientation of small mechanical components that arrive at the assembly area in unsorted bins. This operation is loosely defined as feeding. Its output is normally a single line of single-orientation components ready to be transported to the assembly area (from a remote but not too distant location) via feedtracks. The next challenge is the presentation of these components to pick-and-place manipulators for their assembly on pallets placed on an indexing machine or a conveyor.

10.6.1 Nonvibratory Feeding

Nonvibratory feeding is the use of devices that do not employ vibration as part of their sorting process; they rely on simple reciprocating or rotary-motion-based mechanisms. The basic requirement is that parts to be sorted must have a very limited number of stable orientations (preferably only two). A stable orientation refers to a static undisturbed orientation of a part when placed on a planar surface—for example, a rectangular prism would have three and a cylinder would have two stable orientations.

Although such feeders differ in their configurations, almost all have a limited-size hopper that acts as a large buffer from which the moving mechanism draws parts. A large number of examples can be found in the publications of Boothroyd et al. Only two cases are presented in this section to provide readers with sufficient understanding of the concept nonvibratory feeding.

Feeding of cylindrical parts: The feeder shown in Fig. 28 employs a one degree-of-freedom (dof) reciprocating mechanism with a semicylindrical concave-cavity (or a V-shaped-cavity) cross section. At every cycle, the reciprocating cavity dips into a "crowd" of cylindrical components and scoops up several of them during its upswing motion. Once at the limit of this upswing motion, the mechanism briefly stops to give a chance to the parts to slide down the tubular feedtrack, whose upper opening is aligned with the cavity of the reciprocating mechanism. As can be noted, parts can be engaged and slide down the tube only in one of their two possible stable orientations. Screws and rivets, and other similar geometry parts, can benefit from such a reciprocating nonvibratory feeder.

Feeding U-shaped parts: The feeder shown in Fig. 29 employs a one-dof rotary mechanism with multiple blades that have rectangular cross sections matching the inner dimension of the U-shaped part. At each cycle, every one of the blades of the rotary mechanism sweeps through the hopper (from the bottom, upward) and engages the U-shaped parts along its curved section. As the mechanism continues its motion, the parts slide down through the blade and move toward its end (straight-line) section. Eventually, the blade aligns itself with an inclined discharge rail and

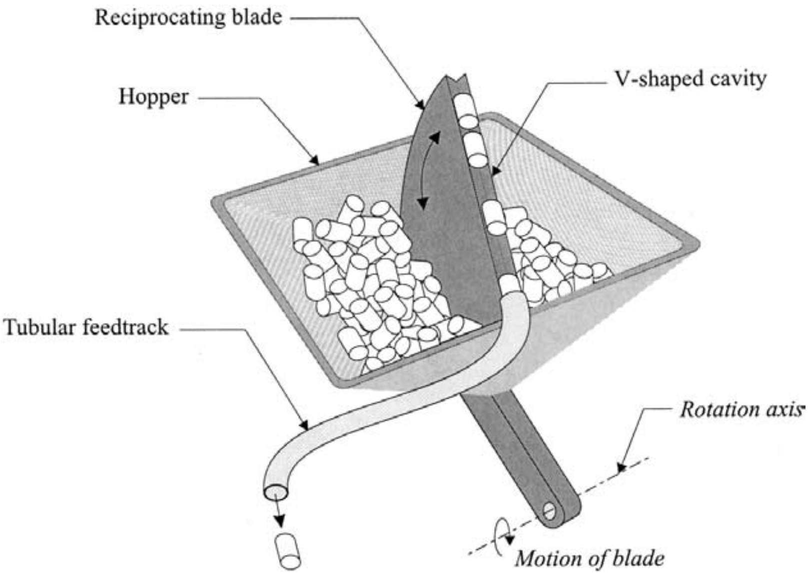


Figure 28 Feeding cylindrical parts.

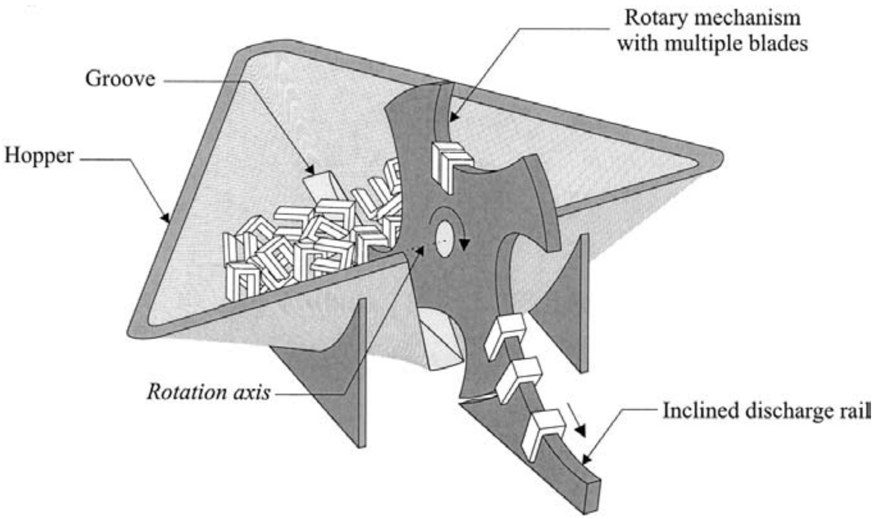


FIGURE 29 Feeding U-shaped parts.

transfers its load. The wheel must be slowed down or stopped completely at the discharge point.

10.6.2 Vibratory Feeding

Vibration has long been used by many industries for the separation and transportation of parts. In automatic assembly, these two objectives are achieved for small mechanical parts using vibratory bowls (Fig. 30a). This feeder device has two primary parts: a vibration-generator base and a replaceable bowl attached to this base through a number of leaf springs. Vibration is generated in two parts, whose combination moves the components upward along a spiral path along the outer wall of the bowl: a torsional vibration about the vertical axis (antigravity) and a translational vibration along this vertical axis (Fig. 30b).

Although parts hop along and move forward owing to the favorable vibration of the bowl, they may reach the end of the spiral path in any one of their stable orientations (preferably but not necessarily on a single line). Thus vibratory feeders must be equipped with orientation devices that would only allow parts with the desired orientation to exit the vibratory bowl. Most such devices employ a variety of attachments or cutouts for passive rejection of the incorrectly oriented parts (i.e., their return into the

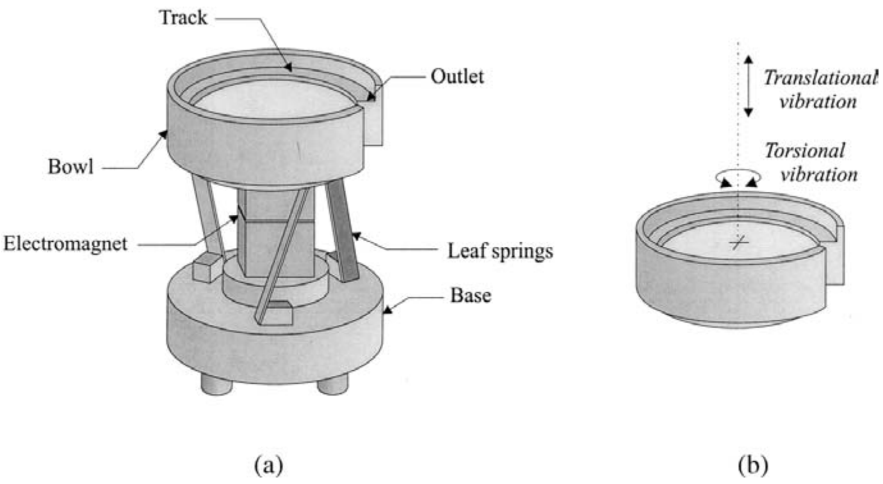


FIGURE 30 (a) Vibratory feeder; (b) vibration axes.

bowl). Naturally, since every stable part orientation would have an associated probability of occurrence, the efficiency of such orientation systems (i.e., the number of parts exiting it versus the number of parts returned back into the bowl) depends on the desired orientation chosen to exit the vibratory bowl. Orientation systems are built externally and normally welded onto the vibratory bowl, replacing an equivalent length section cut out of the last part of the spiral track.

Figure 31a shows an orienting device for screws that have six stable orientations (Fig. 31b). The device has several sections (attachments), each targeted for the rejection of one or more undesirable orientations back into the bowl. The first attachment rejects all parts that are standing up, orientations *a* and *b*; the second attachment narrows the path and thus rejects all parts with orientations *c* and *d*; the geometry of the last attachment not only rejects all parts that are not entering the cutout slot either with their head or tail first, namely all sideways parts, orientations *c* and *d*, that somehow made it to this point, but also it allows all parts that arrived with their head first to reorient themselves into the desired orientation of tail first, orientation *f*; the slot is large enough to let the threaded part of the screws fall through, but narrow enough to hold the head sections and allow the screws to move forward until they engage the discharge hole; once in the hole, the head of the screw must be correctly oriented to slide down, i.e., the cutout must engage the rail that is part of the tube—the torsional vibration

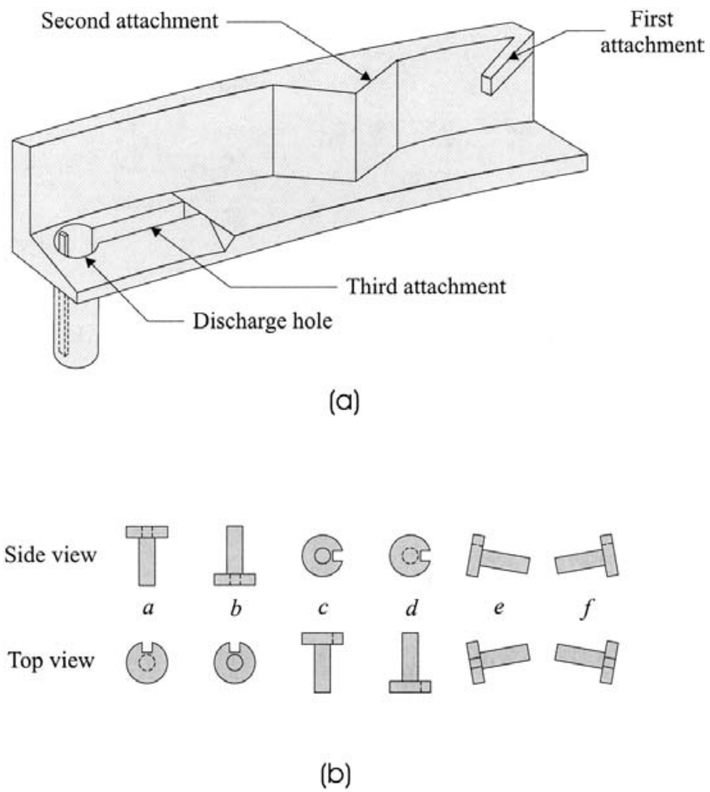


FIGURE 31 (a) Orientation device; (b) stable orientations.

of the bowl would cause the screw to rotate within the tube until this engagement occurs.

As mentioned earlier, the efficiency of the feeding/orientation system shown in Fig. 31 depends on the probability of occurrence of the individual six orientations. Let us say that they are $P_a = 1\%$, $P_b = 5\%$, $P_c = P_d = 12\%$, and $P_e = P_f = 35\%$, for a total of 100%. When 100 screws are dropped onto a hard flat surface, one would have an "*a*" orientation, five would have a "*b*" orientation, etc. Since the orientation device shown in Fig. 31 rejects all orientations *a* to *d*, accepts *f* as is, and reorients *e* into *f*, we would have a (35% + 35% =) 70% efficiency. Thus of 100 parts that randomly enter the orientation device, on average, 70 would exit it with the desired orientation.

Four other orientation devices are shown in Figs. 32a–32d.

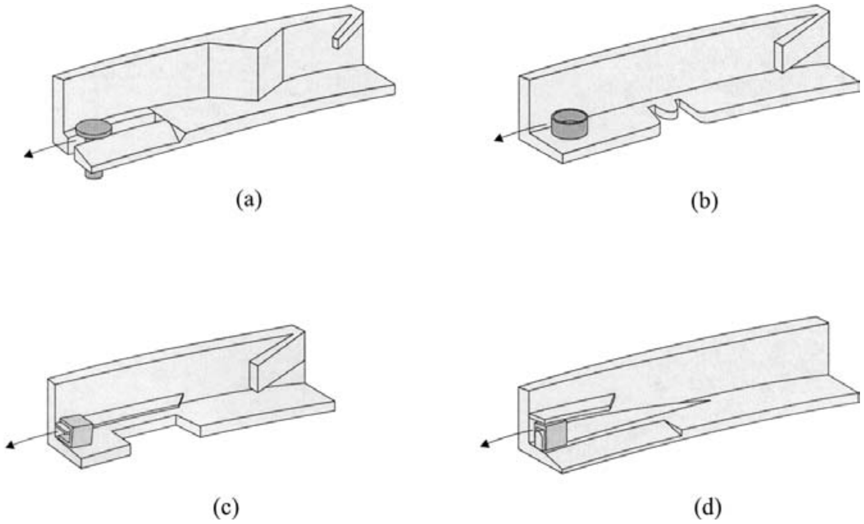


FIGURE 32 Four orientation devices.

10.6.3 Feedtracks and Escapements

Assembly workcell configurations may require sorting machines to be either in the periphery of the assembly area for easy access or noise requirements or as close to a robotic manipulator as needed. In both cases, parts exiting a sorting machine (vibratory or nonvibratory) must be maintained in a single line and desired orientation during their transfer to a designated discharge point. Feedtracks (or discharge rails) used for this purpose must be designed so that they are wide enough to allow fast and jam-free transportation, though narrow enough to prevent parts from changing their orientation during their motion.

Transportation along a feedtrack can be achieved by utilizing gravity or a powered arrangement. Most automatic assembly configurations elevate the sorting machines and allow parts exiting these feeders to slide down the rails via gravity (Fig. 33a).

Powered feedtracks can be of either the vibratory or the pneumatic type. The former vibrates, normally along a horizontal feed track for the forward hopping motion of parts, while the latter utilizes compressed air (input at one or many locations) to accelerate parts on a low-angle gravity track (Figs. 33b and 33c).

An alternative method of supplying an assembly station with sorted parts would be the use of magazines (i.e., finite length, finite capacity, and

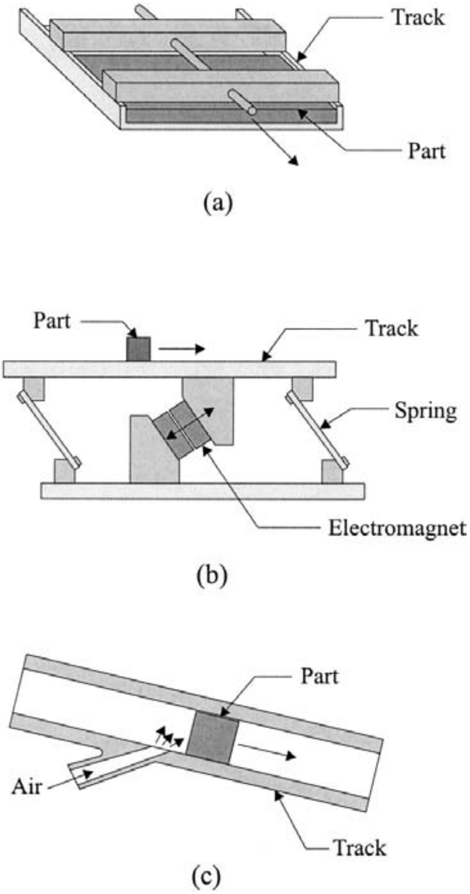


FIGURE 33 Feedtracks: (a) gravity based; (b) vibrational; (c) pneumatic.

transportable feedtracks). Magazines can be filled at remote locations by being attached to a sorting machine or directly to the production machine that is fabricating the parts, thus not necessitating the use of a subsequent sorter. These magazines would then be mounted onto proper fixtures at assembly areas and connected to escapement devices. The use of magazines is very common in the electronics industry, though these should be reusable to be cost effective.

Parts that reach the end of the feedtrack or a magazine must be stopped and presented to the assembler (a robotic manipulator or human operator) at required exact quantities and at exact times or instants. There

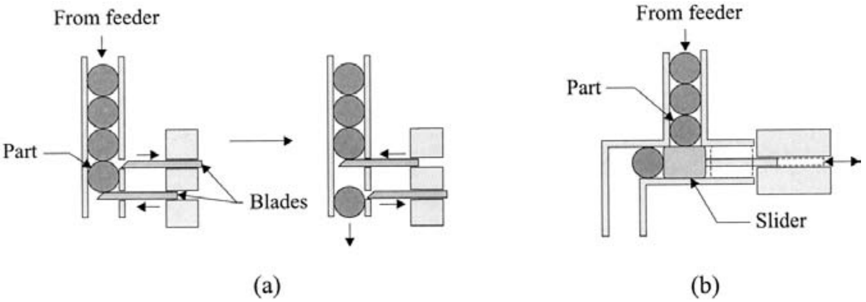


FIGURE 34 (a) Ratchet; (b) slider escapements.

are a variety of industrial escapements (metering devices) that allow the fulfilment of both of these objectives. The most commonly used escapements for vertically stacked parts are the ratchet and slider escapements (Fig. 34).

The ratchet escapement employs two knives (blades) that move in opposite directions: the lower one allows the passage of one (or many) parts, while the upper blade stops the slide of the rest of the waiting parts. The slider escapement utilizes a sliding separator that redirects one or more parts from a vertically stacked column of parts waiting to be dispatched in a feedtrack. For both ratchet and slider escapements, the actions of the dispatchers (blades, blocks, etc.) would be event controlled—i.e., they would execute their motions based on orders received from the controller of the robot that would notify the escapement about a need for the next set of parts (in contrast to a clock-based time control).

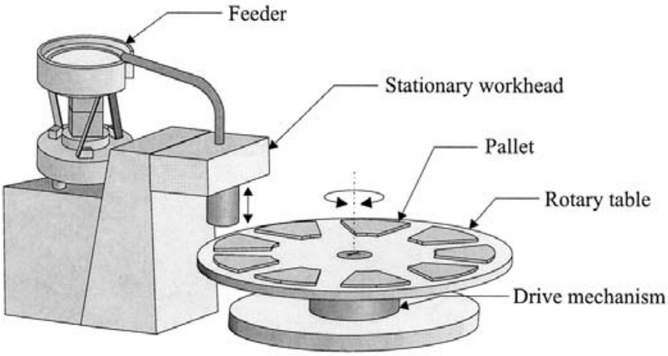
10.6.4 Transfer Equipment

Product assembly via most mechanical joining operations are carried out on pallets equipped with fixtures (Chap. 11) that are stationary or moving at a speed that can be matched by an assembler for on-the-fly assembly. Transfer equipment utilized in transporting these pallets from one assembly station to another (located within a closed vicinity of each other) can be achieved using indexing tables or pallet conveyers (Fig. 35).

A *rotary indexing table* is a circular plate with built-in multiple pallets that is rotated using a drive unit (e.g., ratchet drive, Maltese-cross drive, cam drive, rack-and-pinion drive). The table advances one step (station) forward when all assembly operations at individual stations have been completed—an event-based control.

A *pallet conveyor* is recommended as an intermittent transfer system for applications that require high assembly accuracies. Pallets placed on

Indexing table



Transfer Line

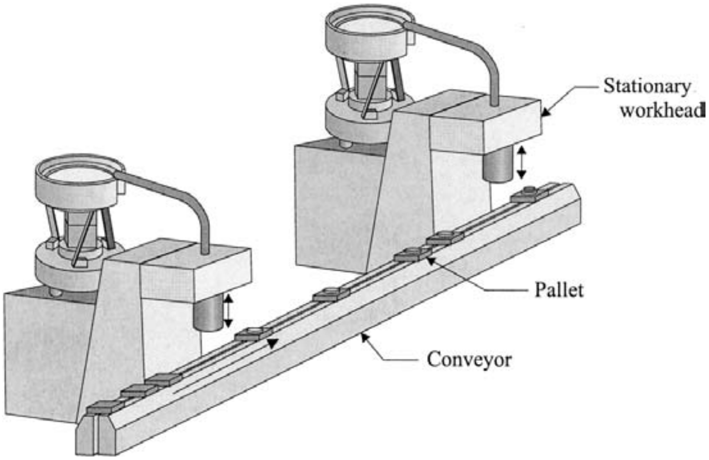


FIGURE 35 Transfer equipment.

such conveyors advance from one station to another by the continuous motion of the conveying medium (e.g., the belt). Once at the desired location, the pallet is stopped and disengaged from the moving conveyor and fixtured accurately by a pallet raiser. Upon termination of the assembly task, the pallet is returned onto the conveyor and allowed to proceed to the next station.

10.6.5 Positioners

In this section, the term "positioner" is utilized to describe nonreprogrammable robotic pick-and-place mechanisms. Such mechanisms are normally low-cost custom-built manipulators with one to three controlled axes of motion (dof). Frequently they are assembled into a desired configuration using a set of modular components (links, actuators, grippers, etc.). Their

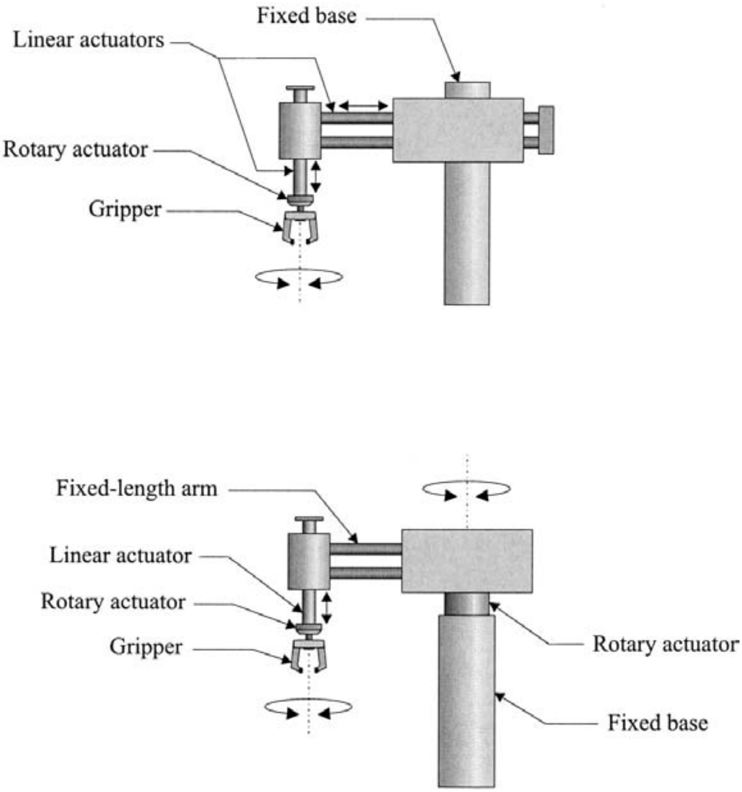


FIGURE 36 Pick-and-place manipulators.

objective is to move mechanical components from one location (e.g., feedtrack) to another (e.g., pallet) in a point-to-point motion at the highest possible speed. For cost effectiveness, the motions of the joints (for example, powered via pressurized air) are not controlled between the two end-of-motion points that are specified by hard stops (with possible built-in mechanical switches).

Two 2-dof pick-and-place mechanism configurations are shown in Fig. 36. Other reprogrammable robot configurations will be discussed in detail in Chap. 12 of this book in the larger context of material handling for a variety of manufacturing applications, including the assembly of small and large parts.

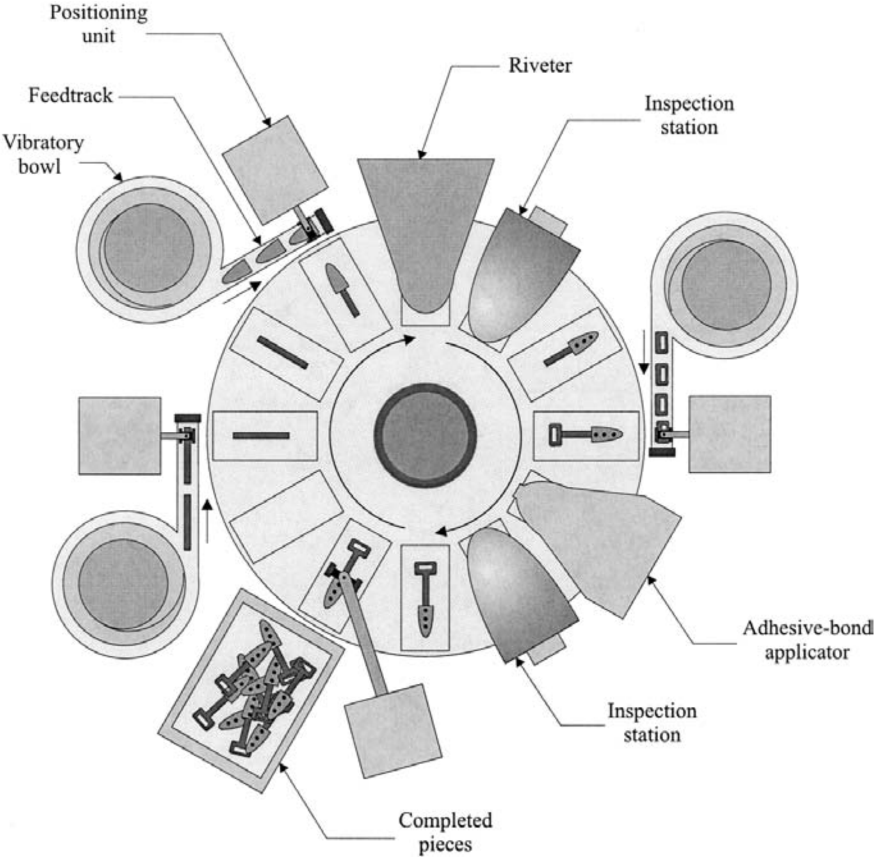


FIGURE 37 An automatic assembly workcell.

In conclusion to the description of the automatic assembly process (Secs. 10.6.1 to 10.6.5), an example assembly workcell that utilizes multiple vibratory bowl feeders, positioners, and numerous joining equipment to assemble a product on an indexing table is shown in Fig. 37.

10.6.6 Design for Automatic Assembly

Assembly has been defined in this chapter as a manufacturing operation that adds cost to a product more than it adds value. The first guideline of design for assembly, thus, has always been to minimize the number of parts that must be joined when assembling a product. Boothroyd et al. set the

Open spring-lock washer will entangle.

Closed spring-lock washer will entangle only under pressure.

Straight slot will entangle.

Crank slot will not entangle.

Parts will nest.

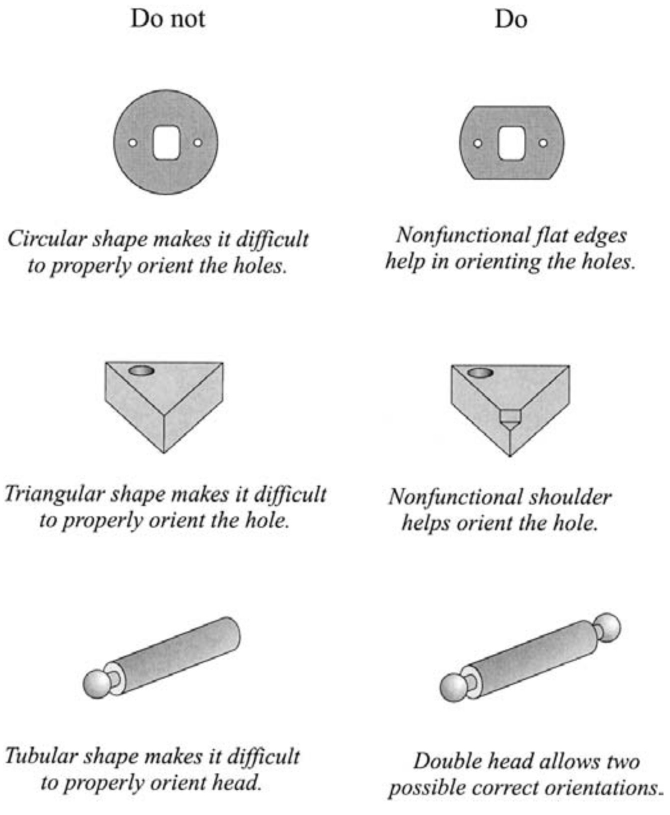
Rib in part prevents nesting.

FIGURE 38 Part feeding guidelines.

following three criteria for whether a part needs to exist as a separate entity from others in the product:

Does the part need to have mobility after assembly?
Does the part need to be of different material or separated from others, owing to reasons such as electrical insulation?
Does the part obstruct or prevent the joining of other parts?

In this section, we will review an exemplary set of secondary guidelines that a product designer must be aware of when configuring part geometries for automatic assembly of small mechanical parts. The order of presentation will be in conformity with the typical order of tasks carried out sequentially: feeding, orienting, transporting, and positioning for joining.



Circular shape makes it difficult to properly orient the holes.

Nonfunctional flat edges help in orienting the holes.

Triangular shape makes it difficult to properly orient the hole.

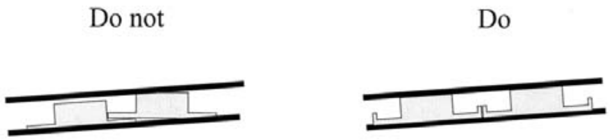
Nonfunctional shoulder helps orient the hole.

Tubular shape makes it difficult to properly orient head.

Double head allows two possible correct orientations.

FIGURE 39 Part orienting guidelines.

Feeding: Parts that arrive in bulk and deposited into (vibratory or non vibratory) feeders must be separated using vibration or mechanical mixing and be maintained free of each other prior to their orientation. Part geometries must not have features (projections, slots, etc.) that will cause tangling, nesting, jamming, etc. (Fig. 38). Nonfunctional features can be added to parts to facilitate feeding.



Wider edge surface prevents overlap.

Nonfunctional peg prevents jamming.

Flat ends prevent jamming.

Wider surface area at contact points prevents overlap.

FIGURE 40 Part transportation guidelines.

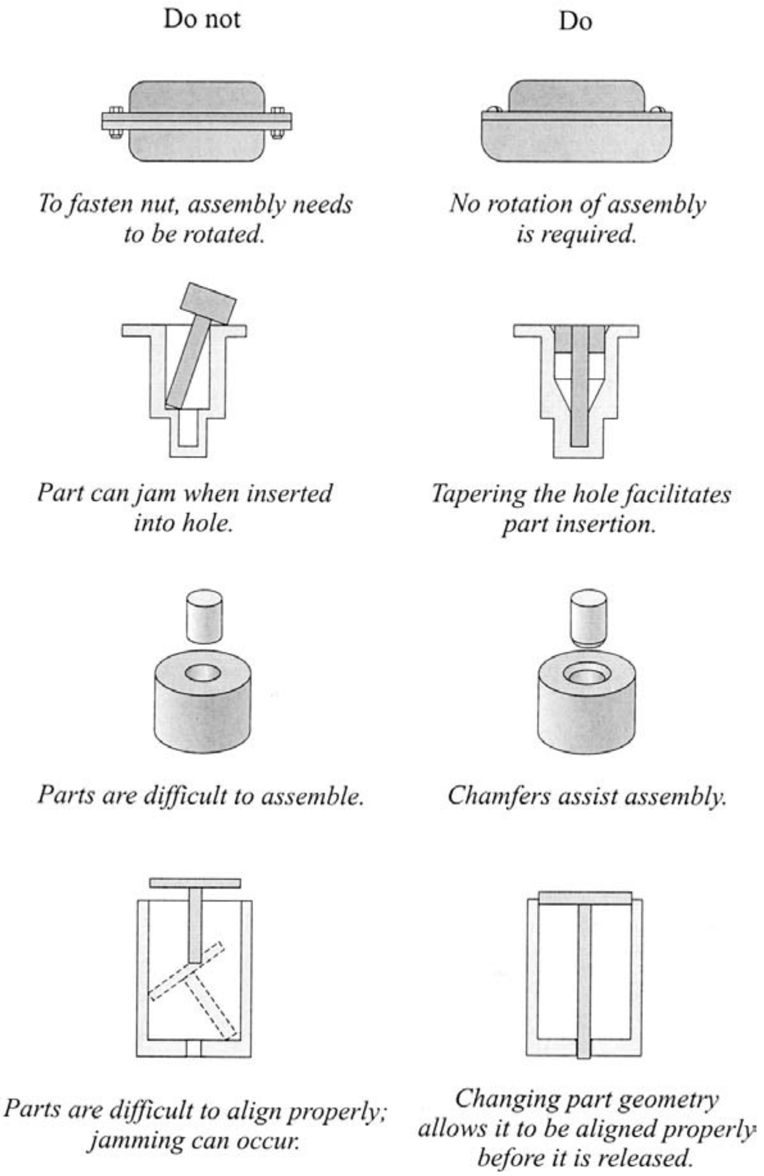


FIGURE 41 Part positioning guidelines.

Orienting: Although mechanical part orienting systems can be manufactured to high tolerances, it is strongly advised to design parts with complete symmetry or exaggerated asymmetry. As in feeding, designers should consider adding nonfunctional features to a part to facilitate automatic orientation, especially in vibratory environments (Fig. 39). An added benefit for such an approach would be ease of recognition of correct assembly orientation by a human assembler.

Transporting: Feedtracks need to be designed and manufactured in their narrowest possible configurations in order to maintain part orientation during transportation. Thus parts must be designed to cooperate with this objective for jam-free transportation (Fig. 40).

Positioning and assembly: The primary requirement of automatic assembly is layered joining. That is, parts should be joined in a minimum number of different orientations. This will reduce costs of fixturing and positioning—requiring robotic manipulators with fewer dof. The second requirement is ease of insertion/mating—parts should have chamfers, self-locating features, tapers, etc. (Fig. 41).

For manual assembly, part designs should also consider the limited dexterity of the human hand (parts should not be too small or slippery) and the safety of the operator (not too sharp).

REVIEW QUESTIONS

1. Why are most products assembled by manufacturers, as opposed to being sold unassembled, even though assembly is seen as a cost-adding process?
2. Define interchangeability of parts for profitable manufacturing.
3. Define the three primary principles of design for assembly.
4. When would mechanical fastening be preferable to other joining methods?
5. Discuss the two conflicting interests in choosing the locations of mechanical fasteners: marketability (aesthetics) versus ease of assembly.
6. Many fasteners used in product assembly could have an unnecessarily large number of threads, thus prolonging the joining process. Argue both sides of this issue. You may further refer to Chap. 7 for similar concerns in die setups (quick die exchange).
7. What are the two common corrosion protection mechanisms for fasteners?
8. What does permanency imply in riveting, in contrast to in adhesive bonding, in soldering, etc.?
9. What are the primary advantages/disadvantages of adhesive bonding? Discuss its potential use in aviation industries versus riveting.

10. Discuss the following two issues in adhesive bonding: overlapping of the joints and joint thickness.
11. Why is surface preparation the most important step in adhesive bonding?
12. Define fusion welding versus solid-state welding.
13. Why should welding regions be shielded using inert gases?
14. Compare shielded metal arc welding (SMAW) to gas metal arc welding (GMAW).
15. Why would one use nonconsumable electrodes in arc welding (e.g., GTAW)?
16. Discuss the advantages of laser-beam welding.
17. Why should brazing and soldering not be considered welding operations? What is the primary difference between brazing and soldering?
18. Describe the wetting process and its importance in brazing and soldering.
19. What is the purpose of using a flux in the soldering process?
20. What is the eutectic composition of the tin–lead alloy and why do electronics manufacturers prefer to use it for soldering?
21. What is the principal similarity/difference between reflow soldering and infrared (reflow) soldering?
22. Describe the ball-grid array (BGA) packaging technology used in the electronics industry.
23. What are the primary steps of assembly of small mechanical components when using nonprogrammable (vibratory or nonvibratory) feeding devices?
24. How do parts move forward in the spiral track of a vibratory feeder?
25. What are stable part orientations? How would one use probability data about stable part orientations in designing orienting systems for vibratory feeders?
26. Discuss the design of effective feedtracks for optimal part transportation.
27. Discuss the use of magazines in parts assembly.
28. Discuss the three criteria proposed by Boothroyd et al. in evaluating whether a part needs to exist as a unique component or whether it could be joined to another in order to reduce the number of parts in a product.

DISCUSSION QUESTIONS

1. Assembly is often viewed as a cost-adding operation as opposed to fabrication, which is viewed as a value-adding operation. Discuss this issue in the context of several exemplary products: computers and automobiles that are preassembled versus furniture that is sold for “some assembly” by the customers.
2. The majority of mechanical joining techniques yield nonpermanent joints (i.e., those that can be removed without destroying the joining

elements and/or damaging the joined components). Discuss the advantages/disadvantages of such joints (when compared to permanent joints, such as rivets, adhesive joints, soldered joints, welded joints, etc.) in various operational conditions (static versus dynamic).

3. Welding, soldering, and painting are a few manufacturing operations that rely on the maintenance of consistent and repeatable process parameters. Discuss the use of automation (including the use of industrial robots) for these and other processes that have similar requirements as replacements for manual labor.
4. Nonfunctional features on a product facilitate their manual (or even automatic) assembly. Discuss some generic feature characteristics for such purposes. Furthermore, examine some consumer products whose daily use could be facilitated by such features (e.g., near-square cookie boxes with not-connected lids, door handles, etc.).
5. Process planning in assembly (in its limited definition) is the optimal selection of an assembly sequence of the components. For example, solving the traveling salesperson problem in the population of electronics boards. Although there exist a number of search techniques for the solution of such problems, they could all benefit from the existence of a good initial (guess) solution. Discuss the role of group technology (GT) on the identification of such initial (guesses) sequences of assembly.
6. Analysis of an assembly process via computer-aided modeling and simulation can lead to an optimal process plan with significant savings in assembly time and cost. Discuss the issue of time and resources spent on obtaining an optimal plan and the actual (absolute) savings obtained due to this optimization: for example, spending several hours in planning to reduce assembly time from 2 minutes to 1 minute. Present your analysis as a comparison of one-of-a-kind production versus mass production.
7. Several fabrication/assembly machines can be physically or virtually brought together to yield a manufacturing workcell for the production of a family of parts. Discuss the advantages of adopting a cellular manufacturing strategy in contrast to having a departmentalized strategy, i.e., having a turning department, a milling department, a grinding department, etc. Among others, an important issue to consider is the transportation of parts (individually or in batches).
8. Human factors (HF) studies encompass a range of issues spanning from ergonomics to human–machine (including human–software) interfaces. Discuss the role of HF in the autonomous factory of the future, where the impact of human operators is significantly diminished and emphasis is switched from operating machines to supervision, planning, and maintenance.

9. During the 20th century, there have been statements and graphical illustrations implying that product variety and batch size remain in conflict in the context of profitable manufacturing. Discuss recent counterarguments that advocate profitable manufacturing of a high variety of products in a mass-production environment. Furthermore, elaborate on an effective facility layout that can be used in such environments: job shop, versus cellular, versus flow line, versus a totally new approach.

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