CHAPTER 5
NICKEL AND ITS ALLOYS

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5.1 INTRODUCTION

Nickel, the 24th element in abundance, has an average content of 0.016% in the outer 10 miles of the earth's crust. This is greater than the total for copper, zinc, and lead. However, few of these deposits scattered throughout the world are of commercial importance. Oxide ores commonly called laterites are largely distributed in the tropics. The igneous rocks contain high magnesium contents and have been concentrated by weathering. Of the total known ore deposits, more than 80% is contained in laterite ores. The sulfide ores found in the northern hemispheres do not easily concentrate by weathering. The sulfide ores in the Sudbury district of Ontario, which contain important by-products such as copper, cobalt, iron, and precious metals are the world's greatest single source of nickel.[1]

Nickel has an atomic number of 28 and is one of the transition elements in the fourth series in the periodic table. The atomic weight is 58.71 and density is 8.902 g/cm^3. Useful properties of the element are the modulus of elasticity and its magnetic and magnetostrictive properties, and high thermal and electrical conductivity. Hydrogen is readily adsorbed on the surface of nickel. Nickel will also adsorb other gases such as carbon monoxide, carbon dioxide, and ethylene. It is this capability of surface adsorption of certain gases without forming stable compounds that makes nickel an important catalyst.[2]

As an alloying element, nickel is used in hardenable steels, stainless steels, special corrosion-resistant and high-temperature alloys, copper–nickel, "nickel–silvers," and aluminum–nickel. Nickel imparts ductility and toughness to cast iron.

Approximately 10% of the total annual production of nickel is consumed by electroplating processes. Nickel can be electrodeposited to develop mechanical properties of the same order as wrought nickel; however, special plating baths are available that will yield nickel deposits possessing a hardness as high as 450 Vickers (425 BHN). The most extensive use of nickel plate is for corrosion protection of iron and steel parts and zinc-base die castings used in the automotive field. For these applications, a layer of nickel, 0.0015–0.003 in. thick, is used. This nickel plate is then finished or covered with a chromium plate consisting in thickness of about 1% of the underlying nickel plate thickness in order to maintain a brilliant, tarnish-free, hard exterior surface.

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5.2 NICKEL ALLOYS

Most of the alloys listed and discussed are in commercial production. However, producers from time to time introduce improved modifications that make previous alloys obsolete. For this reason, or economic reasons, they may remove certain alloys from their commercial product line. Some of these alloys have been included to show how a particular composition compares with the strength or corrosion resistance of currently produced commercial alloys.

5.2.1 Classification of Alloys

Nickel and its alloys can be classified into the following groups on the basis of chemical composition.[3]

Nickel

(1) Pure nickel, electrolytic (99.56% Ni), carbonyl nickel powder and pellet (99.95% Ni); (2) commercially pure wrought nickel (99.6–99.97% nickel); and (3) anodes (99.3% Ni).

Nickel and Copper

(1) Low-nickel alloys (2–13% Ni); (2) cupronickels (10–30% Ni); (3) coinage alloy (25% Ni); (4) electrical resistance alloy (45% Ni); (5) nonmagnetic alloys (up to 60% Ni); and (6) high-nickel alloys, Monel (over 50% Ni).

Nickel and Iron

Wrought alloy steels (0.5–9% Ni); (2) cast alloy steels (0.5–9% Ni); (3) alloy cast irons (1–6 and 14–36% Ni); (4) magnetic alloys (20–90% Ni): (a) controlled coefficient of expansion (COE) alloys (29.5–32.5% Ni) and (b) high-permeability alloys (49–80% Ni); (5) nonmagnetic alloys (10–20% Ni); (6) clad steels (5–40% Ni); (7) thermal expansion alloys: (a) low expansion (36–50% Ni) and (b) selected expansion (22–50% Ni).

Iron, Nickel, and Chromium

(1) Heat-resisting alloys (40–85% Ni); (2) electrical resistance alloys (35–60% Ni); (3) iron-base superalloys (9–26% Ni); (4) stainless steels (2–25% Ni); (5) valve steels (2–13% Ni); (6) iron-base superalloys (0.2–9% Ni); (7) maraging steels (18% Ni).

Nickel, Chromium, Molybdenum, and Iron

(1) Nickel-base solution-strengthened alloys (40–70% Ni); (2) nickel-base precipitation-strengthened alloys (40–80% Ni).

Powder-Metallurgy Alloys

(1) Nickel-base dispersion strengthened (78–98% Ni); (2) nickel-base mechanically alloyed oxide-dispersion-strengthened (ODS) alloys (69–80% Ni).

The nominal chemical composition of nickel-base alloys is given in Table 5.1. This table does not include alloys with less than 30% Ni, cast alloys, or welding products. For these and those alloys not listed, the chemical composition and applicable specifications can be found in the *Unified Numbering System for Metals and Alloys*, published by the Society of Automotive Engineers, Inc.

5.2.2 Discussion and Applications

The same grouping of alloys used in Tables 5.1, 5.2, and 5.3, which give chemical composition and mechanical properties, will be used for discussion of the various attributes and uses of the alloys as a group. Many of the alloy designations are registered trademarks of producer companies.

Nickel Alloys

The corrosion resistance of nickel makes it particularly useful for maintaining product purity in the handling of foods, synthetic fibers, and caustic alkalies, and also in structural applications where resistance to corrosion is a prime consideration. It is a general-purpose material used when the special properties of the other nickel alloys are not required. Other useful features of the alloy are its magnetic and magnetostrictive properties; high thermal and electrical conductivity; low gas content; and low vapor pressure.[4]

Typical *nickel 200* applications are food-processing equipment, chemical shipping drums, electrical and electronic parts, aerospace and missile components, caustic handling equipment and piping, and transducers.

Nickel 201 is preferred to nickel 200 for applications involving exposure to temperatures above 316°C (600°F). Nickel 201 is used as coinage, plater bars, and combustion boats in addition to some of the applications for Nickel 200.

Permanickel alloy 300 by virtue of the magnesium content is age-hardenable. But, because of its low alloy content, alloy 300 retains many of the characteristics of nickel. Typical applications are

Table 5.1 Nonimal Chemical Composition (wt%)

Material	Ni	Cu	Fe	Cr	Mo	Al	Ti	Nb	Mn	Si	C	Other Elements
Nickel												
Nickel 200	99.6	—	—	—	—	—	—	—	0.23	0.03	0.07	—
Nickel 201	99.7	—	—	—	—	—	—	—	0.23	0.03	0.01	—
Permanickel alloy 300	98.7	—	0.02	—	—	—	0.49	—	0.11	0.04	0.29	0.38 Mg
Duranickel alloy 301	94.3	—	0.08	—	—	4.44	0.44	—	0.25	0.50	0.16	—
Nickel–Copper												
Monel alloy 400	65.4	32	1.00	—	—	—	—	—	1.0	0.10	0.12	—
Monel alloy 404	54.6	45.3	0.03	—	—	—	—	—	0.01	0.04	0.07	—
Monel alloy R-405	65.3	31.6	1.25	—	—	0.1	—	—	1.0	0.17	0.15	0.04 S
Monel alloy K-500	65.0	30	0.64	—	—	2.94	0.48	—	0.70	0.12	0.17	—
Nickel–Chromium–Iron												
Inconel alloy 600	76	0.25	8.0	15.5	—	—	—	—	0.5	0.25	0.08	—
Inconel alloy 601	60.5	0.50	14.1	23.0	—	1.35	—	—	0.5	0.25	0.05	—
Inconel alloy 690	60	—	9.0	30	—	—	—	—	—	—	0.01	—
Inconel alloy 706	41.5	0.15	40	16	—	0.20	1.8	3	0.18	0.18	0.03	—
Inconel alloy 718	53.5	0.15	18.5	19	3.0	0.5	0.9	5.1	0.18	—	0.04	—
Inconel alloy X-750	73	0.25	7	15.5	—	0.70	2.5	1	0.50	0.25	0.04	—
Nickel–Iron–Chromium												
Incoloy alloy 800	31	0.38	46	20	—	0.38	0.38	—	0.75	0.50	0.05	—
Incoloy alloy 800H	31	0.38	46	20	—	0.38	0.38	—	0.75	0.50	0.07	—
Incoloy alloy 825	42	1.75	30	22.5	3	0.10	0.90	—	0.50	0.25	0.01	—
Incoloy alloy 925	43.2	1.8	28	21	3	0.35	2.10	—	0.60	0.22	0.03	—
Pyromet 860	44	—	Bal	13	6	1.0	3.0	—	0.25	0.10	0.05	4.0 Co
Refractaloy 26	38	—	Bal	18	3.2	0.2	2.6	—	0.8	1.0	0.03	20 Co
Nickel–Iron												
Nilo alloy 36	36	—	61.5	—	—	—	—	—	0.5	0.09	0.03	
Nilo alloy 42	41.6	—	57.4	—	—	—	—	—	0.5	0.06	0.03	—
Ni–Span–C alloy 902	42.3	0.05	48.5	5.33	—	0.55	2.6	—	0.40	0.50	0.03	—
Incoloy alloy 903	38	—	41.5	—	—	0.90	1.40	2.9	0.09	0.17	0.02	14 Co
Incoloy alloy 907	37.6	0.10	41.9	—	—	1.5	—	4.70	0.05	0.08	0.02	14 Co

Table 5.1 (*Continued*)

Material	Ni	Cu	Fe	Cr	Mo	Al	Ti	Nb	Mn	Si	C	Other Elements
Nickel–Chromium–Molybdenum												
Hastelloy alloy X	Bal[c]	—	19	22	9	—	—	—	—	—	0.10	—
Hastelloy alloy G	Bal	2	19.5	22	6.5	—	—	2.1	<1	1.5	<0.05	<1 W, <2.5 Co
Hastelloy alloy C-276	Bal	—	5.5	15.5	16	—	—	—	<0.08	<1	<0.01	2.5 Co, 4 W, 0.35 V
Hastelloy alloy C	Bal	—	<3	16	15.5	—	<0.7	—	<0.08	<1	<0.01	<2 Co
Inconel alloy 617	54	—	—	22	9	1	—	—	—	—	0.07	12.5 Co
Inconel alloy 625	Bal	—	2.5	21.5	9	<0.4	<0.4	3.6	—	—	0.03	—
MAR-M-252	Bal	—	—	19	10	1	2.6	—	<0.5	<0.5	0.15	10 Co, 0.005 B
Rene' 41	Bal	—	—	19	10	1.5	3.1	—	—	—	0.09	11 Co <0.010 B
Rene' 95	Bal	—	—	14	3.5	3.5	2.5	3.5	—	—	0.15	8 Co, 3.5 W, 0.01 B, 0.05 Zr
Astroloy	Bal	—	—	15	5.3	4.4	3.5	—	—	—	0.06	15 Co
Udimet 500	Bal	—	<0.5	19	4	3.0	3.0	—	—	—	0.08	18 Co 0.007 B
Udimet 520	Bal	—	—	19	6	2.0	3.0	—	—	—	0.05	12 Co. 1 W, 0.005 B
Udimet 600	Bal	—	<4	17	4	4.2	2.9	—	—	—	0.04	16 Co. 0.02 B
Udimet 700	Bal	—	—	15	5.0	4.4	3.5	—	—	—	0.07	18.5 Co, 0.025 B
Udimet 1753	Bal	—	9.5	16.3	1.6	1.9	3.2	—	0.1	0.05	0.24	7.2 Co, 8.4 W, 0.008 B, 0.06 Zr
Waspaloy	Bal	<0.1	<2	19	4.3	1.5	3	—	—	—	0.08	14 Co, 0.006 B, 0.05 Zr
Nickel-Powder Alloys (Dispersion Strengthened)												
TD–nickel	98	—	—	—	—	—	—	—	—	—	—	2 ThO_2
TD–NiCr	Bal	—	—	20	—	—	—	—	—	—	—	1.7 ThO_2
Nickel-Powder Alloys (Mechanically Alloyed)												
Inconel alloy MA 754	78	—	1.0	20	—	0.3	0.5	—	—	—	0.05	0.6 Y_2O_3
Inconel alloy MA 6000	69	—	—	15	2	4.5	2.5	—	—	—	0.05	4 W, 2 Ta, 1.1 Y_2O_3

[a] Minimum. [b] Maximum. [c] Balance.

Table 5.2 Mechanical Properties of Nickel Alloys

Material	0.2% Yield Strength (ksi)[a]	Tensile Strength (ksi)[a]	Elongation (%)	Rockwell Hardness
Nickel				
Nickel 200	21.5	67	47	55 Rb
Nickel 201	15	58.5	50	45 Rb
Permanickel alloy 300	38	95	30	79 Rb
Duranickel alloy 301	132	185	28	36 Rc
Nickel–Copper				
Monel alloy 400	31	79	52	73 Rb
Monel alloy 404	31	69	40	68 Rb
Monel alloy R-405	56	91	35	86 Rb
Monel alloy K-500	111	160	24	25 Rc
Nickel–Chromium–Iron				
Inconel alloy 600	50	112	41	90 Rb
Inconel alloy 601	35	102	49	81 Rb
Inconel alloy 690	53	106	41	97 Rb
Inconel alloy 706	158	193	21	40 Rc
Inconel alloy 718	168	205	20	46 Rc
Inconel alloy X-750	102	174	25	33 Rc
Nickel–Iron–Chromium				
Incoloy alloy 800	48	88	43	84 Rb
Incoloy alloy 800H	29	81	52	72 Rb
Incoloy alloy 825	44	97	53	84 Rb
Incoloy alloy 925	119	176	24	34 Rc
Pyromet 860	115	180	21	37 Rc
Refractaloy 26	100	170	18	—
Nickel–Iron				
Nilo alloy 42	37	72	43	80 Rb
Ni–Span–C alloy 902	137	150	12	33 Rc
Incoloy alloy 903	174	198	14	39 Rc
Incoloy alloy 907	163	195	15	42 Rc
Nickel–Chromium–Molybdenum				
Hastelloy alloy X	52	114	43	—
Hastelloy alloy G	56	103	48.3	86 Rb
Hastelloy alloy C-276	51	109	65	—
Inconel alloy 617	43	107	70	81 Rb
Inconel alloy 625	63	140	51	96 Rb
MAR-M-252	122	180	16	—
Rene′ 41	120	160	18	—
Rene′ 95	190	235	15	—
Astroloy	152	205	16	—
Udimet 500	122	190	32	—
Udimet 520	125	190	21	—
Udimet 600	132	190	13	—
Udimet 700	140	204	17	—
Udimet 1753	130	194	20	39 Rc
Waspaloy	115	185	25	—
Nickel-Powder Alloys (Dispersion Strengthened)				
TD–Nickel	45	65	15	—
TD–NiCr	89	137	20	—
Nickel-Powder Alloys (Mechanically Alloyed)				
Inconel alloy MA 754	85	140	21	—
Inconel alloy MA 6000	187	189	3.5	—

[a] MPa = ksi × 6.895.

Table 5.3 1000-hr Rupture Stress (ksi)[a]

	1200°F	1500°F	1800°F	2000°F
Nickel–Chromium–Iron				
Inconel alloy 600	14.5	3.7	1.5	—
Inconel alloy 601	28	6.2	2.2	1.0
Inconel alloy 690	16	—	—	—
Inconel alloy 706	85	—	—	—
Inconel alloy 718	85	—	—	—
Inconel alloy X-750	68	17	—	—
Nickel–Iron–Chromium				
Incoloy alloy 800	20	—	—	—
Incoloy alloy 800H	23	6.8	1.9	0.9
Incoloy alloy 825	26	6.0	1.3	—
Pyromet 860	81	17	—	—
Refractaloy 26	65	15.5	—	—
Nickel–Chromium–Moloybdenum				
Hastelloy alloy X	31	9.5	—	—
Inconel alloy 617	52	14	3.8	1.5
Inconel alloy 625	60	7.5	—	—
MAR-M-252	79	22.5	—	—
Rene′ 41	102	29	—	—
Rene′ 95	125	—	—	—
Astroloy	112	42	8	—
Udimet 500	110	30	—	—
Udimet 520	85	33	—	—
Udimet 600	—	37	—	—
Udimet 700	102	43	7.5	—
Udimet 1753	98	34	6.5	—
Waspaloy	89	26	—	—
Nickel-Powder Alloys (Dispersion Strengthened)				
TD–Nickel	21	15	10	7
TD–NiCr	—	—	8	5
Nickel-Powder Alloys (Mechanically Alloyed)				
Inconel alloy MA 754	38	—	19	14
Inconel alloy MA 6000	—	—	22	15

[a] MPa ksi × 6.895.

grid lateral winding wires, magnetostriction devices, thermostat contact arms, solid-state capacitors, grid side rods, diaphragms, springs, clips, and fuel cells.

Duranickel alloy 301 is another age-hardenable high nickel alloy, but is made heat treatable by aluminum and titanium additions. The important features of alloy 301 are high strength and hardness, good corrosion resistance, and good spring properties up to 316°C (600°F); and it is on these mechanical considerations that selection of the alloy is usually based. Typical applications are extrusion press parts, molds used in the glass industry, clips, diaphragms, and springs.

Nickel–Copper Alloys

Nickel–copper alloys are characterized by high strength, weldability, excellent corrosion resistance, and toughness over a wide temperature range. They have excellent service in seawater or brackish water under high-velocity conditions, as in propellers, propeller shafts, pump shafts, and impellers and condenser tubes, where resistance to the effects of cavitation and erosion are important. Corrosion rates in strongly agitated and aerated seawater usually do not exceed 1 mil/year.

Monel alloy 400 has low corrosion rates in chlorinated solvents, glass-etching agents, sulfuric and many other acids, and practically all alkalies, and it is resistant to stress-corrosion cracking. Alloy 400 is useful up to 538°C (1000°F) in oxidizing atmospheres, and even higher temperatures may be used if the environment is reducing. Springs of this material are used in corrosive environments up to 232°C (450°F). Typical applications are valves and pumps; pump and propeller shafts; marine fixtures and fasteners; electrical and electronic components; chemical processing equipment; gasoline and freshwater tanks; crude petroleum stills, process vessels, and piping; boiler feedwater heaters and other heat exchangers; and deaerating heaters.

Monel alloy 404 is characterized by low magnetic permeability and excellent brazing characteristics. Residual elements are controlled at low levels to provide a clean, wettable surface even after prolonged firing in wet hydrogen. Alloy 404 has a low Curie temperature and its magnetic properties are not appreciably affected by processing or fabrication. This magnetic stability makes alloy 404 particularly suitable for electronic applications. Much of the strength of alloy 404 is retained at outgassing temperatures. Thermal expansion of alloy 404 is sufficiently close to that of many other alloys as to permit the firing of composite metal tubes with negligible distortion. Typical applications are waveguides, metal-to-ceramic seals, transistor capsules, and power tubes.

Monel alloy R-405 is a free-machining material intended almost exclusively for use as stock for automatic screw machines. It is similar to alloy 400 except that a controlled amount of sulfur is added for improved machining characteristics. The corrosion resistance of alloy R-405 is essentially the same as that of alloy 400, but the range of mechanical properties differs slightly. Typical applications are water meter parts, screw machine products, fasteners for nuclear applications, and valve seat inserts.

Monel alloy K-500 is an age-hardenable alloy that combines the excellent corrosion resistance characteristics of the Monel nickel–copper alloys with the added advantage of increased strength and hardness. Age hardening increases its strength and hardness. Still better properties are achieved when the alloy is cold-worked prior to the aging treatment. Alloy K-500 has good mechanical properties over a wide temperature range. Strength is maintained up to about 649°C (1200°F), and the alloy is strong, tough, and ductile at temperatures as low as −253°C (−423°F). It also has low permeability and is nonmagnetic to −134°C (−210°F). Alloy K-500 has low corrosion rates in a wide variety of environments. Typical applications are pump shafts and impellers, doctor blades and scrapers, oil-well drill collars and instruments, electronic components, and springs.

Nickel–Chromium–Iron Alloys

This family of alloys was developed for high-temperature oxidizing environments. These alloys typically contain 50–80% nickel, which permits the addition of other alloying elements to improve strength and corrosion resistance while maintaining toughness.

Inconel alloy 600 is a standard engineering material for use in severely corrosive environments at elevated temperatures. It is resistant to oxidation at temperatures up to 1177°C (2150°F). In addition to corrosion and oxidation resistance, alloy 600 presents a desirable combination of high strength and workability, and is hardened and strengthened by cold-working. This alloy maintains strength, ductility, and toughness at cryogenic as well as elevated temperatures. Because of its resistance to chloride-ion stress-corrosion cracking and corrosion by high-purity water, it is used in nuclear reactors. For this service, the alloy is produced to exacting specifications and is designated Inconel alloy 600T. Typical applications are furnace muffles, electronic components, heat-exchanger tubing, chemical- and food-processing equipment, carburizing baskets, fixtures and rotors, reactor control rods, nuclear reactor components, primary heat-exchanger tubing, springs, and primary water piping. Alloy 600, being one of the early high-temperature, corrosion-resistant alloys, can be thought of as being the basis of many of our present day special-purpose high-nickel alloys, as illustrated in Fig. 5.1.

Inconel alloy 601 has shown very low rates of oxidation and scaling at temperatures as high as 1093°C (2000°F). The high chromium content (nominally 23%) gives alloy 601 resistance to oxidizing, carburizing, and sulfur-containing environments. Oxidation resistance is further enhanced by the aluminum content. Typical applications are heat-treating baskets and fixtures, radiant furnace tubes, strand-annealing tubes, thermocouple protection tubes, and furnace muffles and retorts.

Inconel alloy 690 is a high-chromium nickel alloy having very low corrosion rates in many corrosive aqueous media and high-temperature atmospheres. In various types of high-temperature water, alloy 690 also displays low corrosion rates and excellent resistance to stress-corrosion cracking—desirable attributes for nuclear steam-generator tubing. In addition, the alloy's resistance to sulfur-containing gases makes it a useful material for such applications as coal-gasification units, burners and ducts for processing sulfuric acid, furnaces for petrochemical processing, and recuperators and incinerators.

Inconel alloy 706 is a precipitation-hardenable alloy with characteristics similar to alloy 718, except that alloy 706 has considerably improved machinability. It also has good resistance to oxidation and corrosion over a broad range of temperatures and environments. Like alloy 718, alloy 706 has excellent resistance to postweld strain-age cracking. Typical applications are gas-turbine components and other parts that must have high strength combined with good machinability and weldability.

Inconel alloy 718 is an age-hardenable high-strength alloy suitable for service at temperatures from −253°C (−423°F) to 704°C (1300°F). The fatigue strength of alloy 718 is high, and the alloy exhibits high stress-rupture strength up to 704°C (1300°F) as well as oxidation resistance up to 982°C (1800°F). It also offers good corrosion resistance to a wide variety of environments. The outstanding characteristic of alloy 718 is its slow response to age hardening. The slow response enables the material to be welded and annealed with no spontaneous hardening unless it is cooled slowly. Alloy 718 can also be repair-welded in the fully aged condition. Typical applications are jet engine components, pump bodies and parts, rocket motors and thrust reversers, and spacecraft.

Inconel alloy X-750 is an age-hardenable nickel–chromium–iron alloy used for its corrosion and oxidation resistance and high creep-rupture strength up to 816°C (1500°F). The alloy is made age-hardenable by the addition of aluminum, columbium, and titanium, which combine with nickel, during

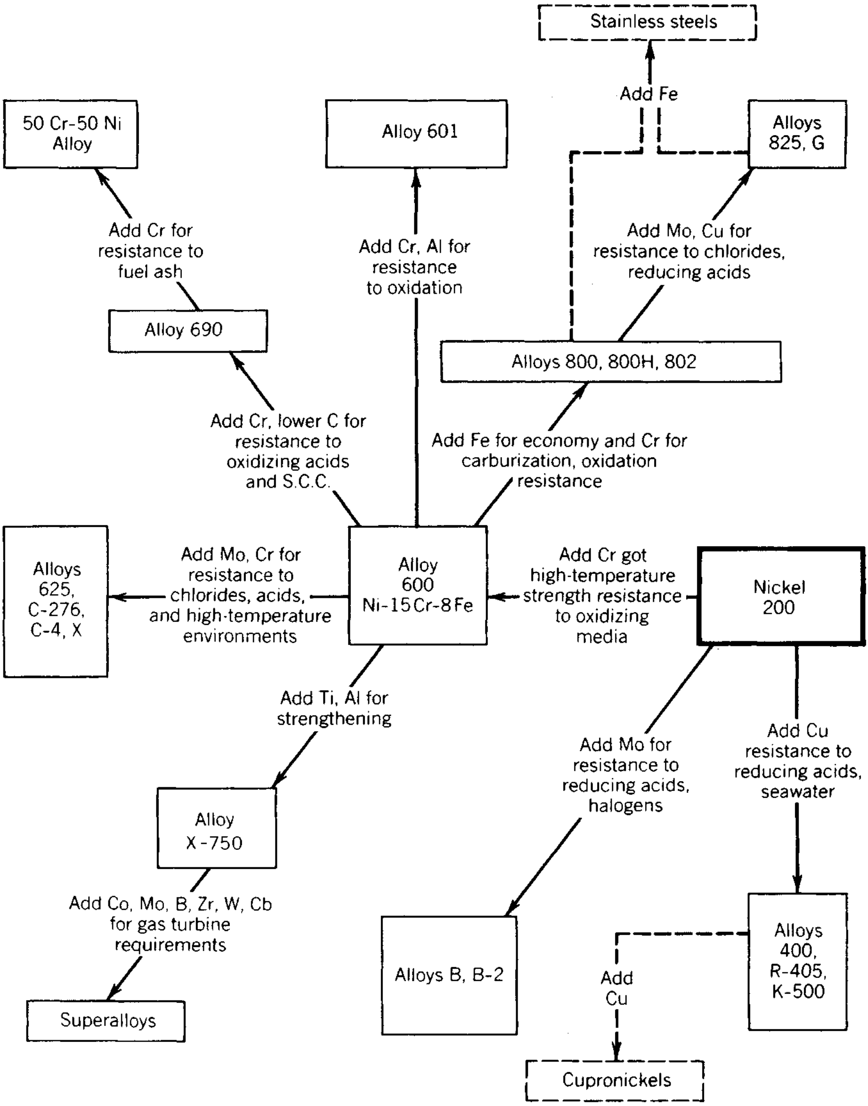

Fig. 5.1 Some compositional modifications of nickel and its alloys to produce special properties.

proper heat treatment, to form the intermetallic compound $Ni_3(Al, Ti)$. Alloy X-750, originally developed for gas turbines and jet engines, has been adopted for a wide variety of other uses because of its favorable combination of properties. Excellent relaxation resistance makes alloy X-750 suitable for springs operating at temperatures up to about 649°C (1200°F). The material also exhibits good strength and ductility at temperatures as low as −253°C (−423°F). Alloy X-750 also exhibits high resistance to chloride-ion stress-corrosion cracking even in the fully age-hardened condition. Typical applications are gas-turbine parts (aviation and industrial), springs (steam service), nuclear reactors, bolts, vacuum envelopes, heat-treating fixtures, extrusion dies, aircraft sheet, bellows, and forming tools.

Nickel–Iron–Chromium Alloys

This series of alloys typically contains 30–45% Ni and is used in elevated- or high-temperature environments where resistance to oxidation or corrosion is required.

Incoloy alloy 800 is a widely used material of construction for equipment that must resist corrosion, have high strength, or resist oxidation and carburization. The chromium in the alloy imparts resistance to high-temperature oxidation and general corrosion. Nickel maintains an austenitic structure so that the alloy remains ductile after elevated-temperature exposure. The nickel content also contributes resistance to scaling, general corrosion, and stress-corrosion cracking. Typical applications are heat-treating equipment and heat exchangers in the chemical, petrochemical, and nuclear industries, especially where resistance to stress-corrosion cracking is required. Considerable quantities are used for sheathing on electric heating elements.

Incoloy alloy 800H is a version of Incoloy alloy 800 having significantly higher creep and rupture strength. The two alloys have the same chemical composition with the exception that the carbon content of alloy 800H is restricted to the upper portion of the standard range for alloy 800. In addition to a controlled carbon content, alloy 800H receives an annealing treatment that produces a coarse grain size—an ASTM number of 5 or coarser. The annealing treatment and carbon content are responsible for the alloy's greater creep and rupture strength.

Alloy 800H is useful for many applications involving long-term exposure to elevated temperatures or corrosive atmospheres. In chemical and petrochemical processing, the alloy is used in steam/hydrocarbon reforming for catalyst tubing, convection tubing, pigtails, outlet manifolds, quenching-system piping, and transfer piping; in ethylene production for both convection and cracking tubes; in oxo-alcohol production for tubing in hydrogenation heaters; in hydrodealkylation units for heater tubing; and in production of vinyl chloride monomer for cracking tubes, return bends, and inlet and outlet flanges.

Industrial heating is another area of wide usage for alloy 800H. In various types of heat-treating furnaces, the alloy is used for radiant tubes, muffles, retorts, and assorted furnace fixtures. Alloy 800H is also used in power generation for steam superheater tubing and high-temperature heat exchangers in gas-cooled nuclear reactors.

Incoloy alloy 825 was developed for use in aggressively corrosive environments. The nickel content of the alloy is sufficient to make it resistant to chloride-ion stress-corrosion cracking, and, with molybdenum and copper, alloy 825 has resistance to reducing acids. Chromium confers resistance to oxidizing chemicals. The alloy also resists pitting and intergranular attack when heated in the critical sensitization temperature range. Alloy 825 offers exceptional resistance to corrosion by sulfuric acid solutions, phosphoric acid solutions, and seawater. Typical applications are phosphoric acid evaporators, pickling-tank heaters, pickling hooks and equipment, chemical-process equipment, spent nuclear fuel element recovery, propeller shafts, tank trucks, and oil-country cold-worked tubulars.

Incoloy alloy 925 was developed for severe conditions found in corrosive wells containing H_2S, CO_2, and brine at high pressures. Alloy 925 is a weldable, age-hardenable alloy having corrosion and stress-corrosion resistance similar to Incoloy alloy 825. It is recommended for applications where alloy 825 does not have adequate yield or tensile strength for service in the production of oil and gas, such as valve bodies, hanger bars, flow lines, casing, and other tools and equipment.

Pyromet 860 and *Refractaloy 26* are high-temperature precipitation-hardenable alloys with lower nickel content than Inconel alloy X-750 but with additions of cobalt and molybdenum. The precipitation-hardening elements are the same except the Al/Ti ratio is reversed with titanium content being greater than aluminum. Typical applications of both alloys are critical components of gas turbines, bolts, and structural members.[8]

Nickel–Iron

The nickel–iron alloys listed in Table 5.1 as a group have a low coefficient of expansion that remains virtually constant to a temperature below the Curie temperature for each alloy. A major application for *Nilo alloy 36* is tooling for curing composite airframe components. The thermal expansion characteristics of *Nilo alloy 42* are particularly useful for semiconductor lead frames and glass-sealing applications.

Ni-Span-C alloy 902 and *Incoloy alloys 903 and 907* are precipitation-hardenable alloys with similar thermal expansion characteristics to Nilo alloy 42 but having different constant coefficient of expansion temperature range. Alloy 902 is frequently used in precision apparatus where elastic members must maintain a constant frequency when subjected to temperature fluctuations. Alloys 903 and 907 are being used in aircraft jet engines for members requiring high-temperature strengths to 649°C (1200°F) with thermal expansion controlled to maintain low clearance.

Nickel–Chromium–Molybdenum Alloys

This group of alloys contains 45–60% Ni and was developed for severe corrosion environments. Many of these alloys also have good oxidation resistance and some have useful strength to 1093°C (2000°F).

Hastelloy alloy X is a non-age-hardenable nickel–chromium–iron–molybdenum alloy developed for high-temperature service up to 1204°C (2200°F). Typical applications are furnace hardware subjected to oxidizing, reducing, and neutral atmospheres; aircraft jet engine tail pipes; and combustion cans and afterburner components.[5,6]

Hastelloy alloy C is a mildly age-hardenable alloy similar in composition to alloy X except nearly all the iron is replaced with molybdenum and nickel. It is highly resistant to strongly oxidizing acids, salts, and chlorine. It has good high-temperature strength. Typical applications are chemical, petrochemical, and oil refinery equipment; aircraft jet engines; and heat-treating equipment.[6,7]

Hastelloy alloy C-276 is a modification of Hastelloy alloy C where the carbon and silicon content is reduced to very low levels to diminish carbide precipitation in the heat-affected zone of weldments. Alloy C-276 is non-age-hardenable and is used in the solution-treated condition. No postwelding heat treatment is necessary for chemical-process equipment. Typical applications are chemical- and petrochemical-process equipment, aircraft jet engines, and deep sour gas wells.[6,7]

Hastelloy alloy G is a non-age-hardenable alloy similar to the composition of alloy X but with 2% copper and 2% columbium and lower carbon content. Alloy G is resistant to pitting and stress-corrosion cracking. Typical applications are paper and pulp equipment, phosphate fertilizer, and synthetic fiber processing.[6,7]

Inconel alloy 617 is a solid-solution-strengthened alloy containing cobalt that has an exceptional combination of high-temperature strength and oxidation resistance which makes alloy 617 a useful material for gas-turbine aircraft engines and other applications involving exposure to extreme temperatures, such as, steam generator tubing and pressure vessels for advanced high-temperature gas-cooled nuclear reactors.

Inconel alloy 625, like alloy 617, is a solid-solution-strengthened alloy but containing columbium instead of cobalt. This combination of elements is responsible for superior resistance to a wide range of corrosive environments of unusual severity as well as to high-temperature effects such as oxidation and carburization. The properties of alloy 625 that make it attractive for seawater applications are freedom from pitting and crevice corrosion, high corrosion fatigue strength, high tensile strength, and resistance to chloride-ion stress-corrosion cracking. Typical applications are wire rope for mooring cables; propeller blades; submarine propeller sleeves and seals; submarine snorkel tubes; aircraft ducting, exhausts, thrust-reverser, and spray bars; and power plant scrubbers, stack liners, and bellows.

MAR-M-252, Rene' 41, Rene' 95, and *Astroloy* are a group of age-hardenable nickel-base alloys containing 10–15% cobalt designed for highly stressed parts operating at temperatures from 871 to 982°C (1600 to 1800°F) in jet engines. MAR-M-252 and Rene' 41 have nearly the same composition but Rene' 41 contains more of the age-hardening elements allowing higher strengths to be obtained. Rene' 95, of similar base composition but in addition containing 3.5% columbium and 3.5% tungsten, is used at temperatures between 371 and 649°C (700 and 1200°F). Its primary use is as disks, shaft retaining rings, and other rotating parts in aircraft engines of various types.[6–8]

Udimet 500, 520, 600, and 700 and *Unitemp 1753* are age-hardenable, nickel-base alloys having high strength at temperatures up to 982°C (1800°F). All contain a significant amount of cobalt. Applications include jet engine gas-turbine blades, combustion chambers, rotor disks, and other high-temperature components.[6–8]

Waspaloy is an age-hardenable nickel-base alloy developed to have high strength up to 760°C (1400°F) combined with oxidation resistance to 871°C (1600°F). Applications are jet engine turbine buckets and disks, air frame assemblies, missile systems, and high-temperature bolts and fasteners.[6–8]

Nickel Powder Alloys (Dispersion Strengthened)

These oxide dispersion strengthened (ODS) alloys are produced by a proprietary powder metallurgical process using thoria as the dispersoid. The mechanical properties to a large extent are determined by the processing history. The preferred thermomechanical processing results in an oriented texture with grain aspect ratios of about 3:1 to 6:1.

TD–nickel and *TD–NiCr* are dispersion-hardened nickel alloys developing useful strengths up to 1204°C (2200°F). These alloys are difficult to fusion weld without reducing the high-temperature strength. Brazing is used in the manufacture of jet engine hardware. Applications are jet engine parts, rocket nozzles, and afterburner liners.[6–8]

Nickel Powder Alloys (Mechanically Alloyed)

Inconel alloy MA 754 and *Inconel alloy MA 6000* are ODS nickel-base alloys produced by mechanical alloying.[9,10] An yttrium oxide dispersoid imparts high creep-rupture strength up to 1149°C (2100°F). MA 6000 is also age-hardenable, which increases strength at low temperatures up to 760°C (1400°F) These mechanical alloys like the thoria-strengthened alloys described are difficult to fusion weld without reducing high-temperature strength. Useful strength is obtained by brazing. MA 754 is being used as aircraft gas-turbine vanes and bands. Applications for MA 6000 are aircraft gas turbine buckets and test grips.

5.3 CORROSION

It is well recognized that the potential saving is very great by utilizing available and economic practices to improve corrosion prevention and control. Not only should the designer consider initial cost of materials, but he or she should also include the cost of maintenance, length of service, downtime cost, and replacement costs. This type of cost analysis can frequently show that more highly alloyed, corrosion-resistant materials are more cost effective. The National Commission on

Materials Policy concluded that one of the "most obvious opportunities for material economy is control of corrosion."

Studies have shown that the total cost of corrosion is astonishing. The overall cost of corrosion in the United States was estimated by the National Bureau of Standards in 1978 and updated by Battelle scientists in 1995. According to a report released in April, metallic corrosion costs the United States about $300 billion a year. The report, released by Battelle (Columbus, Ohio) and Specialty Steel Industry of North America (SSINA, Washington, DC), claims that about one-third of the costs of corrosion ($100 billion) is avoidable and could be saved by broader use of corrosion-resistant materials and the application of best anticorrosion technology from design through maintenance.

Since becoming commercially available shortly after the turn of the century, nickel has become very important in combating corrosion. It is a major constituent in the plated coatings and claddings applied to steel, corrosion-resistant stainless steels, copper–nickel and nickel–copper alloys, high-nickel alloys, and commercially pure nickel alloys. Not only is nickel a corrosion-resistant element in its own right, but, owing to its high tolerance for alloying, it has been possible to develop many metallurgically stable, special-purpose alloys.[11]

Figure 5.1 shows the relationship of these alloys and the major effect of alloying elements. Alloy 600 with 15% chromium, one of the earliest of the nickel–chromium alloys, can be thought of as the base for other alloys. Chromium imparts resistance to oxidizing environments and high-temperature strength. Increasing chromium to 30%, as in alloy 690, increases resistance to stress-corrosion cracking, nitric acid, steam, and oxidizing gases. Increasing chromium to 50% increases resistance to melting sulfates and vanadates found in fuel ash. High-temperature oxidation resistance is also improved by alloying with aluminum in conjunction with high chromium (e.g., alloy 601).

Without chromium, nickel by itself is used as a corrosion-resistant material in food processing and in high-temperature caustic and gaseous chlorine or chloride environments.

Of importance for aqueous reducing acids, oxidizing chloride environments, and seawater are alloy 625 and alloy C-276, which contain 9% and 16% molybdenum, respectively, and are among the most resistant alloys currently available. Low-level titanium and aluminum additions provide γ' strengthening while retaining good corrosion resistance, as in alloy X-750. Cobalt and other alloying element additions provide jet engine materials (superalloys) that combine high-temperature strength with resistance to gaseous oxidation and sulfidation.

Another technologically important group of materials are the higher-iron alloys, which were originally developed to conserve nickel and are often regarded as intermediate in performance and cost between nickel alloys and stainless steels. The prototype, alloy 800 (Fe/33% Ni/21% Cr), is a general purpose alloy with good high-temperature strength and resistance to steam and oxidizing or carburizing gases. Alloying with molybdenum and chromium, as in alloy 825 and alloy G, improves resistance to reducing acids and localized corrosion in chlorides.

Another important category is the nickel–copper alloys. At the higher-nickel end are the Monel alloys (30–45% Cu, balance Ni) used for corrosive chemicals such as hydrofluoric acid, and severe marine environments. At the higher-copper end are the cupronickels (10–30% Ni, balance Cu), which are widely used for marine applications because of their fouling resistance.

Nickel alloys exhibit high resistance to attack under nitriding conditions (e.g., in dissociated ammonia) and in chlorine or chloride gases. Corrosion in the latter at elevated temperatures proceeds by the formation and volatilization of chloride scales, and high-nickel contents are beneficial since nickel forms one of the least volatile chlorides. Conversely, in sulfidizing environments, high-nickel alloys without chromium can exhibit attack due to the formation of a low-melting-point $Ni\text{-}Ni_3Si_2$ eutectic. However high chromium contents appear to limit this form of attack.[5]

Friend explains corrosion reactions as wet or dry:[11]

> *The term wet corrosion usually refers to all forms of corrosive attack by aqueous solutions of electrolytes, which can range from pure water (a weak electrolyte) to aqueous solutions of acids or bases or of their salts, including neutral salts. It also includes natural environments such as the atmosphere, natural waters, soils, and others, irrespective or whether the metal is in contact with a condensed film or droplets of moisture or is completely immersed. Corrosion by aqueous environments is electrochemical in nature, assuming the presence of anodic and cathodic areas on the surface of the metal even though these areas may be so small as to be indistinguishable by experimental methods and the distance between them may be only of atomic dimensions.*
>
> *The term dry corrosion implies the absence of water or an aqueous solution. It generally is applied to metal/gas or metal/vapor reactions involving gases such as oxygen, halogens, hydrogen sulfide, and sulfur vapor and even to "dry" steam at elevated temperatures. . . . High-temperature oxidation of metals has been considered to be an electrochemical phenomenon since it involves the diffusion of metal ions outward, or of reactant ions inward, through the corrosion product film, accompanied by a flow of electrons.*

The decision to use a particular alloy in a commercial application is usually based on past corrosion experience and laboratory or field testing using test spools of candidate alloys. Most often weight loss is measured to rank various alloys; however, many service failures are due to localized attack such as pitting, crevice corrosion, intergranular corrosion, and stress-corrosion cracking, which must be measured by other means.

A number of investigations have shown the effect of nickel on the different forms of corrosion. Figure 5.2 shows the galvanic series of many alloys in flowing seawater. This series gives an indication of the rate of corrosion between different metals or alloys when they are electrically coupled in an electrolyte. The metal close to the active end of the chart will behave as an anode and corrode, and the metal closer to the noble end will act as a cathode and be protected. Increasing the nickel content will move an alloy more to the noble end of the series. There are galvanic series for other corrosive environments, and the film-forming characteristics of each material may change this series somewhat. Seawater is normally used as a rough guide to the relative positions of alloys in solution of good electrical conductivity such as mineral acids or salts.

Residual stresses from cold rolling or forming do not have any significant effect on the general corrosion rate. However, many low-nickel-containing steels are subject to stress-corrosion cracking in chloride-containing environments. Figure 5.3 from work by LaQue and Copson[12] shows that nickel–chromium and nickel–chromium–iron alloys containing about 45% Ni or more are immune from stress-corrosion cracking in boiling 42% magnesium chloride.[11]

When localized corrosion occurs in well-defined areas, such corrosion is commonly called *pitting attack*. This type of corrosion typically occurs when the protective film is broken or is penetrated by a chloride–iron and the film is unable to repair itself quickly. The addition of chromium and particularly molybdenum makes nickel-base alloys less susceptible to pitting attack, as shown in Fig. 5.4, which shows a very good relationship between critical[11] pitting temperature in a salt solution. Along with significant increases in chromium and/or molybdenum, the iron content must be replaced with more nickel in wrought alloys to resist the formation of embrittling phases.[12,13]

Air *oxidation* at moderately high temperatures will form an intermediate subsurface layer between the alloy and gas quickly. Alloying of the base alloy can affect this subscale oxide and, therefore, control the rate of oxidation. At constant temperature, the resistance to oxidation is largely a function of chromium content. Early work by Eiselstein and Skinner has shown that nickel content is very beneficial under cyclic temperature conditions as shown in Fig. 5.5.[14]

5.4 FABRICATION

The excellent ductility and malleability of nickel and nickel-base alloys in the annealed condition make them adaptable to virtually all methods of cold fabrication. As other engineering properties vary within this group of alloys, formability ranges from moderately easy to difficult in relation to other materials.

5.4.1 Resistance to Deformation

Resistance to deformation, usually expressed in terms of hardness or yield strength, is a primary consideration in cold forming. Deformation resistance is moderately low for the nickel and nickel–copper systems and moderately high for the nickel–chromium and nickel–iron–chromium systems. However, when properly annealed, even the high-strength alloys have a substantial range between yield and ultimate tensile strength. This range is the plastic region of the material and all cold forming is accomplished within the limits of this region. Hence, the high-strength alloys require only stronger tooling and more powerful equipment for successful cold forming. Nominal tensile properties and hardnesses are given in Table 5.2.

5.4.2 Strain Hardening

A universal characteristic of the high-nickel alloys is that they have face-centered-cubic crystallographic structures, and, consequently, are subject to rapid strain hardening. This characteristic is used to advantage in increasing the room-temperature tensile properties and hardness of alloys that otherwise would have low mechanical strength, or in adding strength to those alloys that are hardened by a precipitation heat treatment. Because of this increased strength, large reductions can be made without rupture of the material. However, the number of reductions in a forming sequence will be limited before annealing is required, and the percentage reduction in each successive operation must be reduced.

Since strain hardening is related to the solid-solution strengthening of alloying elements, the strain-hardening rate generally increases with the complexity of the alloy. Accordingly, strain-hardening rates range from moderately low for nickel and nickel–copper alloys to moderately high for nickel–chromium and nickel–iron–chromium alloys. Similarly, the age-hardenable alloys have higher strain-hardening rates than their solid-solution equivalents. Figure 5.6 compares the strain-hardening rates of some nickel alloys with those of other materials as shown by the increase in hardness with increasing cold reduction.

Laboratory tests have indicated that the shear strength of the high-nickel alloys in double shear averages about 65% of the ultimate tensile strength (see Table 5.4). These values, however, were obtained under essentially static conditions using laboratory testing equipment having sharp edges

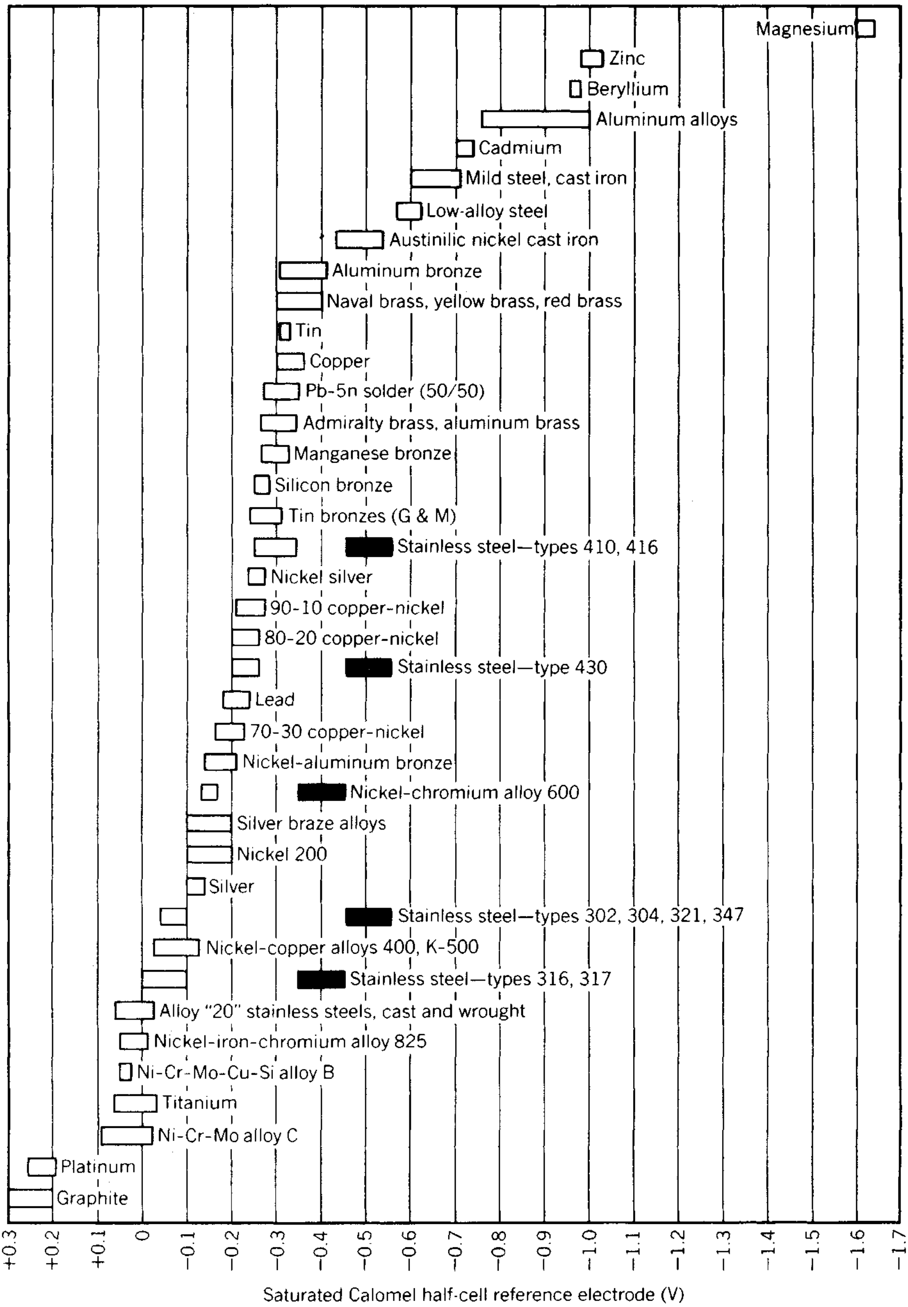

Fig. 5.2 Corrosion potentials in flowing seawater (8-13 ft/sec), temperature range 50-80°F. Alloys are listed in the order of the potential they exhibit in flowing seawater. Certain alloys, indicated by solid boxes, in low velocity or poorly aerated water, and at shielded areas, may become active and exhibit a potential near −0.5 V.

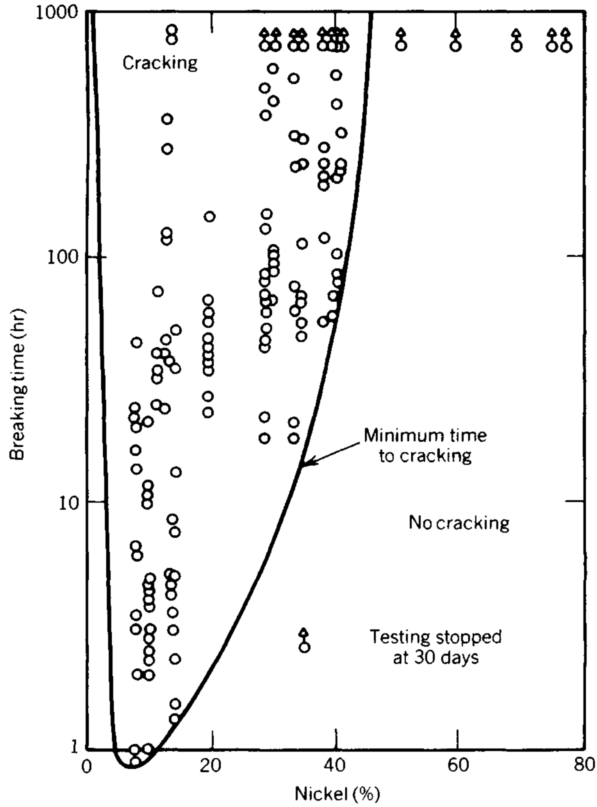

Fig. 5.3 Breaking time of iron–nickel–chromium wires under tensile stress in boiling 42% magnesium chloride.

and controlled clearances. Shear loads for well-maintained production equipment can be found in Table 5.5. These data were developed on a power shear having a 31 mm/m (3/8 in./ft) rake.

5.5 HEAT TREATMENT

High-nickel alloys are subject to surface oxidation unless heating is performed in a protective atmosphere or under vacuum. A protective atmosphere can be provided either by controlling the ratio of fuel and air to minimize oxidation or by surrounding the metal being heated with a prepared atmosphere.

Monel alloy 400, Nickel 200, and similar alloys will remain bright and free from discoloration when heated and cooled in a reducing atmosphere formed by the products of combustion. The alloys that contain chromium, aluminum, or titanium form thin oxide films in the same atmosphere and, therefore, require prepared atmospheres to maintain bright surfaces.

Regardless of the type of atmosphere used, it must be free of sulfur. Exposure of nickel alloys to sulfur-containing atmospheres at high temperatures can cause severe sulfidation damage.

The atmosphere of concern is that in the immediate vicinity of the work, that is, the combustion gases that actually contact the surface of the metal. The true condition of the atmosphere is determined by analyzing gas samples taken at various points about the metal surface.

Furnace atmospheres can be checked for excessive sulfur by heating a small test piece of the material, for example, 13 mm (½ in.) diameter rod or 13 mm × 25 mm (½ in. × 1 in.) flat bar, to the required temperature and holding it at temperature for 10–15 min. The piece is then air cooled or water quenched and bent through 180° flat on itself. If heating conditions are correct, there will be no evidence of cracking.

5.5.1 Reducing Atmosphere

The most common protective atmosphere used in heating the nickel alloys is that provided by controlling the ratio between the fuel and air supplied to the burners. A suitable reducing condition can

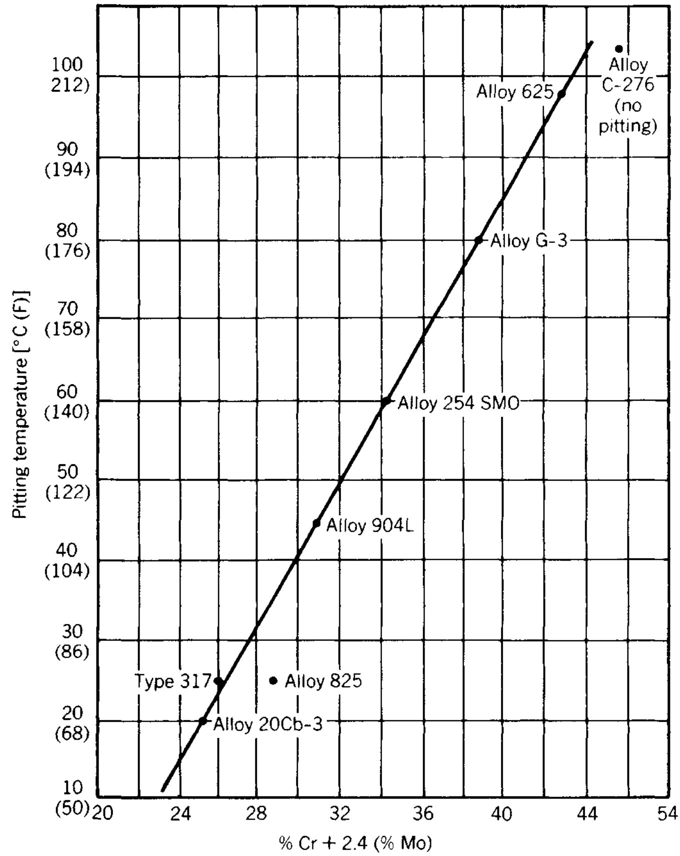

Fig. 5.4 Critical temperature for pitting in 4% NaCl + 1% $Fe_2(SO_4)_3$ + 0.01 *M* HCl versus composition for Fe–Ni–Cr–Mo alloys.

be obtained by using a slight excess of fuel so that the products of combustion contain at least 4%, preferably 6%, of carbon monoxide plus hydrogen. The atmosphere should not be permitted to alternate from reducing to oxidizing; only a slight excess of fuel over air is needed.

It is important that combustion take place before the mixture of fuel and air comes into contact with the work, otherwise the metal may be embrittled. To ensure proper combustion, ample space should be provided to burn the fuel completely before the hot gases contact the work. Direct impingement of the flame can cause cracking.

5.5.2 Prepared Atmosphere

Various prepared atmospheres can be introduced into the heating and cooling chambers of furnaces to prevent oxidation of nickel alloys. Although these atmospheres can be added to the products of combustion in a directly fired furnace, they are more commonly used with indirectly heated equipment. Prepared protective atmospheres suitable for use with the nickel alloys include dried hydrogen, dried nitrogen, dried argon or any other inert gas, dissociated ammonia, and cracked or partially reacted natural gas. For the protection of pure nickel and nickel–copper alloys, cracked natural gas should be limited to a dew point of −1 to 4°C (30 to 40°F).

Figure 5.7 indicates that at a temperature of 1093°C (2000°F), a hydrogen dew point of less than −30°C (−20°F) is required to reduce chromium oxide to chromium; at 815°C (1500°F) the dew point must be below −50°C (−60°F). The values were derived from the thermodynamic relationships of pure metals with their oxides at equilibrium, and should be used only as a guide to the behavior of complex alloys under nonequilibrium conditions. However, these curves have shown a close correlation with practical experience. For example, Inconel alloy 600 and Incoloy alloy 800 are successfully bright-annealed in hydrogen having a dew point of −35 to −40°C (−30 to −40°F).

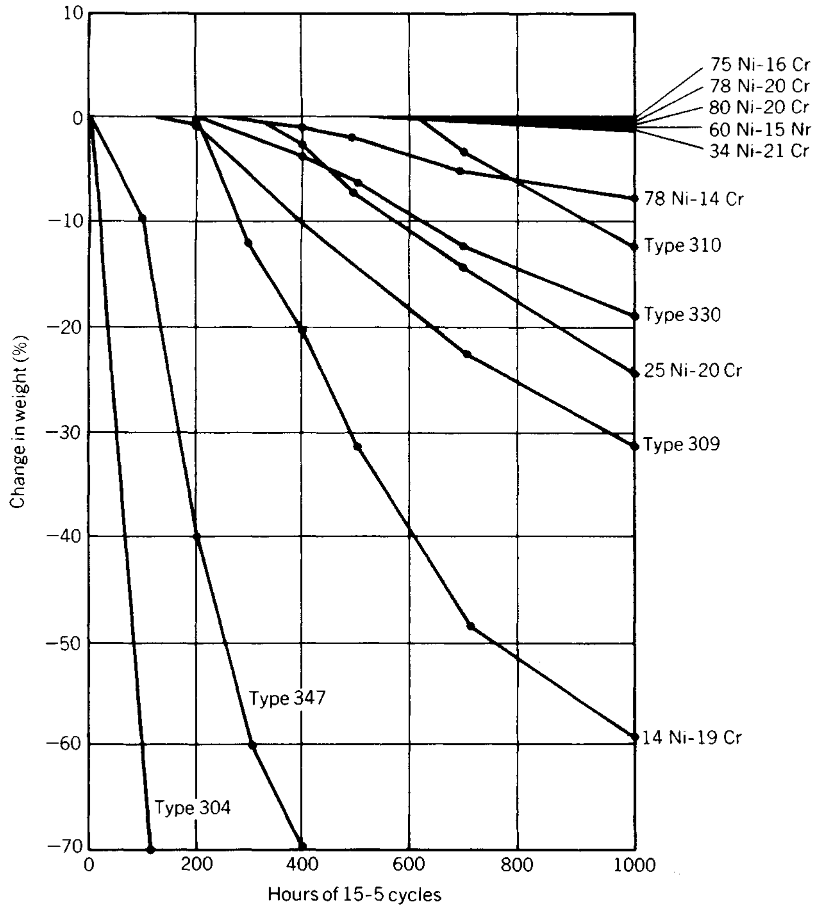

Fig. 5.5 Effect of nickel content on air oxidation of alloys. Each cycle consisted of 15 min at 1800°F followed by a 5-min air cooling.

As indicated in Fig. 5.7, lower dew points are required as the temperature is lowered. To minimize oxidation during cooling, the chromium-containing alloys must be cooled rapidly in a protective atmosphere.

5.6 WELDING

Cleanliness is the single most important requirement for successful welded joints in nickel alloys. At high temperatures, nickel and its alloys are susceptible to embrittlement by sulfur, phosphorus, lead, and other low-melting-point substances. Such substances are often present in materials used in normal manufacturing/fabrication processes; some examples are grease, oil, paint, cutting fluids, marking crayons and inks, processing chemicals, machine lubricants, and temperature-indicating sticks, pellets, or lacquers. Since it is frequently impractical to avoid the use of these materials during processing and fabrication of the alloys, it is mandatory that the metal be thoroughly cleaned prior to any welding operation or other high-temperature exposure.

Before maintenance welding is done on high-nickel alloys that have been in service, products of corrosion and other foreign materials must be removed from the vicinity of the weld. Clean, bright base metal should extend 50–75 mm (2–3 in.) from the joint on both sides of the material. This prevents embrittlement by alloying of corrosion products during the welding process. Cleaning can be done mechanically by grinding with a fine grit wheel or disk, or chemically by pickling.

5.7 MACHINING

Nickel and nickel-base alloys can be machined by the same techniques used for iron-base alloys. However, higher loads will be imparted to the tooling requiring heavy-duty equipment to withstand

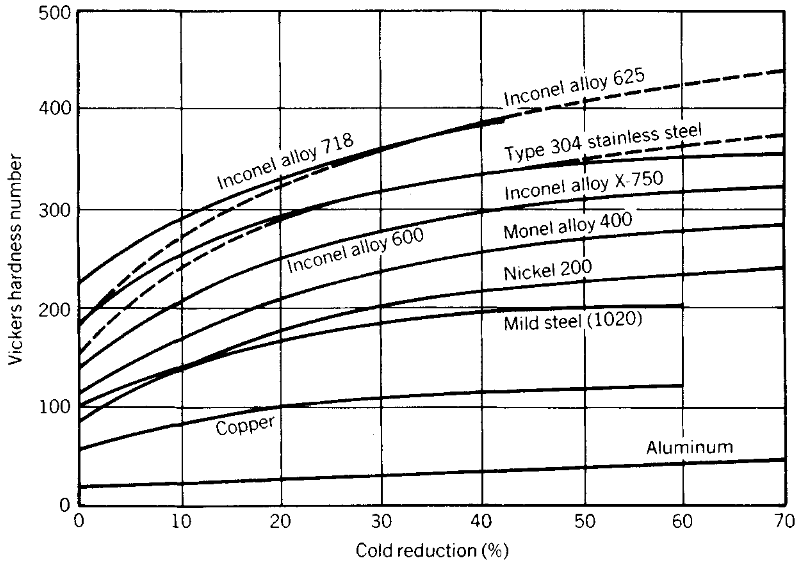

Fig. 5.6 Effect of cold work on hardness.

Table 5.4 Strength in Double Shear of Nickel and Nickel Alloys

Alloy	Condition	Shear Strength (ksi)[a]	Tensile Strength (ksi)	Hardness
Nickel 200	Annealed	52	68	46 Rb
	Half-hard	58	79	84 Rb
	Full-hard	75	121	100 Rb
Monel alloy 400	Hot-rolled, annealed	48	73	65 Rb
	Cold-rolled, annealed	49	76	60 Rb
Inconel alloy 600	Annealed	60	85	71 Rb
	Half-hard	66	98	98 Rb
	Full-Hard	82	152	31 Rc
Inconel alloy X-750	Age-hardened[b]	112	171	36 Re

[a] MPa = ksi × 6.895.
[b] Mill-annealed and aged 1300°F (750°C)/20 hr.

Table 5.5 Shear Load for Power Shearing of 6.35-mm (0.250-in.) Guage Annealed Nickel Alloys at 31 mm/m ($^3/_8$ in./ft.) Rake as Compared with Mild Steel

Alloy	Tensile Strength (ksi)[a]	Hardness (Rb)	Shear Load (lb)[b]	Shear Load in Percent of Same Gauge of Mild Steel
Nickel 200	60	60	61,000	200
Monel alloy 400	77	75	66,000	210
Inconel alloy 600	92	79	51,000	160
Inconel alloy 625	124	95	55,000	180
Inconel alloy 718	121	98	50,000	160
Inconel alloy X-750	111	88	57,000	180
Mild steel	50	60	31,000	100

[a] MPa = ksi × 6.895.
[b] kg = lb × 0.4536.

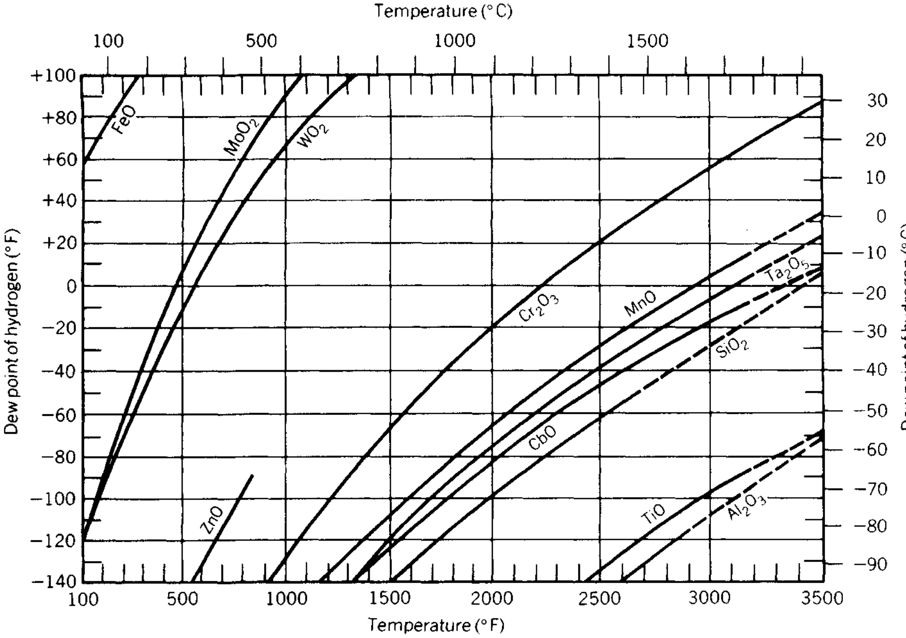

Fig. 5.7 Metal/metal oxide equilibria in hydrogen atmospheres.

Table 5.6 Registered Trademarks of Producer Company

Trademark	Owner
Duranickel	Inco family of companies
Hastelloy	Haynes International, Inc.
Incoloy	Inco family of companies
Inconel	Inco family of companies
MAR-M	Martin Marietta Corp.
Monel	Inco family of companies
Nilo	Inco family of companies
Ni–Span–C	Inco family of companies
Permanickel	Inco family of companies
Pyromet	Carpenter Technology Corp.
Rene	General Electric Co.
Rene' 41	Allvac Metals Corp.
Udimet	Special Metals Corp.
Waspaloy	United Aircraft Corp.

the load and coolants to dissipate the heat generated. The cutting tool edge must be maintained sharp and have the proper geometry.

5.8 CLOSURE

There has been a vast amount of nickel-alloy developments since the 1950 edition of *Kent's Mechanical Engineer's Handbook*. It has not been possible to give the composition and discuss each commercial alloy and, therefore, one should refer to publications like Refs. 6–8 for alloy listings, which are revised periodically to include the latest alloys available. (See Table 5.6 for the producer companies of some of the alloys mentioned in this chapter.)

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