Special-Purpose Nickel Alloys

NICKEL-BASE ALLOYS have a number of unique properties, or combinations of properties, that allow them to be used in a variety of specialized applications. For example, the high resistivity (resistance to flow of electricity) and heat resistance of nickel-chromium alloys lead to their use as electric resistance heating elements. The soft magnetic properties of nickel-iron alloys are employed in electronic devices and for electromagnetic shielding of computers and communication equipment. Iron-nickel alloys have low expansion characteristics as a result of a balance between thermal expansion and magnetostrictive changes with temperature. Originally used as clock pendulums, these alloys are now widely employed as lead frames in packaging electronic chips and as the shadow-masks in color television tubes. On a larger scale, they provide one solution to coping with the thermal expansion requirements of storage and transportation tanks for the growing liquid natural gas industry.

Other properties of interest that expand the markets and applications of nickel and nickel alloys include those to follow:

- Shape memory characteristics of equiatomic nickel-titanium alloys that allow them to be used as actuators, hydraulic connectors, and eyeglass frames
- The high strength at elevated temperature and resistance to stress relaxation that allow wrought nickel-beryllium-titanium to be used for demanding electrical/electronic applications, for example, springs subjected to elevated temperatures (up to 370 °C, or 700 °F) for short times
- The combination of heat removal (high thermal conductivity) and wear resistance that allows cast nickel-beryllium-carbon alloys to be used for tooling for glass forming operations

These and other special-purpose alloys and applications are described subsequently.

Commercially Pure Nickel for Electronic Applications

Commercially pure nickel is available in several grades, slightly different in composition, to meet special needs. The grades considered in this section include the following:

- Nickel 200 (99.6% Ni, 0.04% C)
- Nickel 201 (99.6% Ni, 0.02% C maximum)
- Nickel 205 (99.6% Ni, 0.04% C, 0.04% Mg)
- Nickel 233 (see composition in table that follows)
- Nickel 270 (99.97% Ni)

Composition limits and property data on several of these grades can be found in the article “Wrought Corrosion-Resistant Nickels and Nickel Alloys” in this Handbook.

Nickel 200 and 201. Wrought Nickel 200 (UNS N02200), the general purpose grade, is used for leads and terminals where good strength and toughness at elevated temperature and subzero temperatures are necessary; for transducers (it being one of three metals demonstrating magnetostrictive properties); and for fuel cell and battery plates.

A low-carbon variant, Nickel 201 (UNS N02201), is ideal for deep drawing, etching, spinning, and coining; its rate of work hardening is also low.

Nickel 205. The selected chemistry of Nickel 205 (UNS N02205) results in a high magnetostrictive coefficient and Curie temperature. Its uses have included grid side rods, base pins, anodes, getter tabs, and cathode shields.

Nickel 233 (UNS N02233) is specially produced to the following closely controlled, low-residual-element levels:

Element	Percentage
Carbon	0.15 max
Copper	0.10 max
Iron	0.10 max
Magnesium	0.01–0.10
Manganese	0.30 max
Sulfur	0.008 max
Silicon	0.10 max
Titanium	0.005 max
Nickel	99.00 min

This grade is especially suitable for active cathodes, vacuum tube anodes, and structural parts of tubes.

Nickel 270 (UNS N02270), a high-purity, powder-produced nickel, is 99.97% nickel with a 0.001% maximum limit on cobalt, magnesium, chromium, titanium, sulfur, silicon, manganese, and copper, a 0.005% limit on iron, and a 0.02% limit on carbon. This high purity results in lower coefficient of expansion, electrical resistivity, Curie temperature, and greater ductility than those of other grades of nickel and makes Nickel 270 especially useful for some electronics applications such as components of hydrogen thyratrons and as a substrate for precious metal cladding.

Resistance Heating Alloys

Resistance heating alloys are used in many varied applications—from small household appliances to large industrial process heating systems and furnaces. In appliances or industrial process heating, the heating elements are usually either open helical coils of resistance wire mounted with ceramic bushings in a suitable metal frame, or enclosed metal-sheathed elements consisting of a smaller-diameter helical coil of resistance wire electrically insulated from the metal sheath by compacted refractory insulation. In industrial furnaces, elements often must operate continuously at temperatures as high as 1300 °C (2350 °F) for furnaces used in metal-treating industries, 1700 °C (3100 °F) for kilns used for firing ceramics, and occasionally 2000 °C (3600 °F) or higher for special applications.

Material Requirements. Materials for electric heating depend on an inherent resistance to the flow of electricity to generate heat. Copper wire does not get appreciably hot when carrying electricity because it has good electrical conductivity. Thus for an alloy—as wire, ribbon, or strip—to perform as an electric heating element, it must resist the flow of electricity.

Most of the common steels and alloys such as stainless steels do resist the flow of electricity. The measure of this characteristic is referred to as “electrical resistivity.” It is expressed as either ohm millimeter square per meter ($\Omega \cdot mm^2/m$) in metric units or ohm times circular mils per foot ($\Omega \cdot$ circular mil/ft) in English units.

If resistivity alone was the prime factor for an electric heating element, the choice could be from many alloy candidates in a broad spectrum of cost. However, there are a number of requirements a material must meet in order to avoid failure and provide an extended service

Table 1 Typical properties of resistance heating materials

Basic composition	Resistivity(a), $\Omega \cdot mm^2/m$(b)	Average change in resistance(c), %, from 20 °C to: 260 °C	540 °C	815 °C	1095 °C	Thermal expansion, $\mu m \cdot {}^\circ C$, from 20 °C to: 100 °C	540 °C	815 °C	Tensile strength MPa	ksi	Density g/cm³	lb/in.³
Nickel-chromium and nickel-chromium-iron alloys												
78.5Ni-20Cr-1.5Si (80–20)	1.080	4.5	7.0	6.3	7.6	13.5	15.1	17.6	655–1380	95–200	8.41	0.30
77.5Ni-20Cr-1.5Si-1Nb	1.080	4.6	7.0	6.4	7.8	13.5	15.1	17.6	655–1380	95–200	8.41	0.30
68.5Ni-30Cr-1.5Si (70–30)	1.180	2.1	4.8	7.6	9.8	12.2	…	…	825–1380	120–200	8.12	0.29
68Ni-20Cr-8.5Fe-2Si	1.165	3.9	6.7	6.0	7.1	…	12.6	…	895–1240	130–180	8.33	0.30
60Ni-16Cr-22Fe-1.5Si	1.120	3.6	6.5	7.6	10.2	13.5	15.1	17.6	655–1205	95–175	8.25	0.30
37Ni-21Cr-40Fe-2Si	1.08	7.0	15.0	20.0	23.0	14.4	16.5	18.6	585–1135	85–165	7.96	0.288
35Ni-20Cr-43Fe-1.5Si	1.00	8.0	15.4	20.6	23.5	15.7	15.7	…	550–1205	80–175	7.95	0.287
35Ni-20Cr-42.5Fe-1.5Si-1Nb	1.00	8.0	15.4	20.6	23.5	15.7	15.7	…	550–1205	80–175	7.95	0.287
Iron-chromium-aluminum alloys												
83.5Fe-13Cr-3.25Al	1.120	7.0	15.5	…	…	10.6	…	…	620–1035	90–150	7.30	0.26
81Fe-14.5Cr-4.25Al	1.25	3.0	9.7	16.5	…	10.8	11.5	12.2	620–1170	90–170	7.28	0.26
73.5Fe-22Cr-4.5Al	1.35	0.3	2.9	4.3	4.9	10.8	12.6	13.1	620–1035	90–150	7.15	0.26
72.5Fe-22Cr-5.5Al	1.45	0.2	1.0	2.8	4.0	11.3	12.8	14.0	620–1035	90–150	7.10	0.26
Pure metals												
Molybdenum	0.052	110	238	366	508	4.8	5.8	…	690–2160	100–313	10.2	0.369
Platinum	0.105	85	175	257	305	9.0	9.7	10.1	345	50	21.5	0.775
Tantalum	0.125	82	169	243	317	6.5	6.6	…	345–1240	50–180	16.6	0.600
Tungsten	0.055	91	244	396	550	4.3	4.6	4.6	3380–6480	490–940	19.3	0.697
Nonmetallic heating-element materials												
Silicon carbide	0.995–1.995	–33	–33	–28	–13	4.7	…	…	28	4	3.2	0.114
Molybdenum disilicide	0.370	105	222	375	523	9.2	…	…	185	27	6.24	0.225
$MoSi_2$ + 10% ceramic additives	0.270	167	370	597	853	13.1	14.2	14.8	…	…	5.6	0.202
Graphite	9.100	–16	–18	–13	–8	1.3	…	…	1.8	0.26	1.6	0.057

(a) At 20 °C (68 °F). (b) To convert to Ω·circular mil/ft, multiply by 601.53. (c) Changes in resistance may vary somewhat, depending on cooling rate.

Table 2 Recommended maximum furnace operating temperatures for resistance heating materials

Basic composition, %	Approximate melting point °C	°F	Maximum furnace operating temperature in air °C	°F
Nickel-chromium and nickel-chromium-iron alloys				
78.5Ni-20Cr-1.5Si (80–20)	1400	2550	1150	2100
77.5Ni-20Cr-1.5Si-1Nb	1390	2540		
68.5Ni-30Cr-1.5Si (70–30)	1380	2520	1200	2200
68Ni-20Cr-8.5Fe-2Si	1390	2540	1150	2100
60Ni-16Cr-22Fe-1.5Si	1350	2460	1000	1850
35Ni-30Cr-33.5Fe-1.5Si	1400	2550		
35Ni-20Cr-43Fe-1.5Si	1380	2515	925	1700
35Ni-20Cr-42.5Fe-1.5Si-1Nb	1380	2515		
Iron-chromium-aluminum alloys				
83.5Fe-13Cr-3.25Al	1510	2750	1050	1920
81Fe-14.5Cr-4.25Al	1510	2750		
79.5Fe-15Cr-5.2Al	1510	2750	1260	2300
73.5Fe-22Cr-4.5Al	1510	2750	1280	2335
72.5Fe-22Cr-5.5Al	1510	2750	1375	2505
Pure metals				
Molybdenum	2610	4730	400(a)	750(a)
Platinum	1770	3216	1500	2750
Tantalum	3000	5400	500(a)	930(a)
Tungsten	3400	6150	300(a)	570(a)
Nonmetallic heating-element materials				
Silicon carbide	2410	4370	1600	2900
Molybdenum disilicide	(b)	(b)	1700–1800	3100–3270
$MoSi_2$ + 10% ceramic additives	(b)	(b)	1900	3450
Graphite	3650–3700(b)	6610–6690(c)	400(d)	750(d)

Element	Recommended temperatures: Vacuum	Pure H_2	City gas
Mo	1650 °C (3000 °F)	1760 °C (3200 °F)	1700 °C (3100 °F)
Ta	2480 °C (4500 °F)	Not recommended	Not recommended
W	1650 °C (3000 °F)	2480 °C (4500 °F)	1700 °C (3100 °F)

(a) Recommended atmospheres for these metals are a vacuum of 10^{-4} to 10^{-5} mm Hg, pure hydrogen, and partly combusted city gas dried to a dew point of 4 °C (40 °F). In these atmospheres, the recommended temperatures, would be as shown above. (b) Decomposes before melting at approximately 1740 °C (3165 °F) for $MoSi_2$, and 1825 °C (3315 °F) for $MoSi_2$ + 10% ceramic additives. (c) Graphite volatilizes without melting at 3650 to 3700 °C (6610 to 6690 °F). (d) At approximately 400 °C (750 °F) (threshold oxidation temperature), graphite undergoes a weight loss of 1% in 24 h in air. Graphite elements can be operated at surface temperatures up to 2205 °C (4000 °F) in inert atmospheres.

life. The primary requirements of materials used for heating elements are high melting point, high electrical resistivity, reproducible temperature coefficient of resistance, good oxidation resistance, absence of volatile components, and resistance to contamination. Other desirable properties are good elevated-temperature creep strength, high emissivity, low thermal expansion, and low modulus (both of which help minimize thermal fatigue), good resistance to thermal shock, and good strength and ductility at fabrication temperatures.

Property Data. Four groups of materials are commonly used for high-temperature resistance heating elements: (1) nickel-chromium (Ni-Cr) and nickel-chromium-iron (Ni-Cr-Fe) alloys, (2) iron-chromium-aluminum alloys, (3) refractory metals, and (4) nonmetallic (ceramic) materials. Of these four groups, the Ni-Cr and Ni-Cr-Fe alloys serve by far the greatest number of applications. Table 1 compares the physical and mechanical properties of the four groups. Maximum operating temperatures for resistance heating materials for furnace applications are given in Table 2. Additional property data on some of the Ni-Cr and Ni-Cr-Fe alloys listed in Tables 1 and 2 can be found in data sheets published in the section Properties of Electrical Resistance Alloys in the article "Electrical Resistance Alloys" in *Properties and Selection: Nonferrous Alloys and Special-Purpose Materials*, Volume 2 of the *ASM Handbook*.

The resistivities of Ni-Cr and Ni-Cr-Fe alloys are high, ranging from 1000 to 1187 nΩ · m (600 to 714 Ω · circular mil/ft) at 25 °C. Figure 1 shows that the resistance changes more rapidly with temperature for 35Ni-20Cr-

45Fe than for any other alloy in this group. The curve for 35Ni-30Cr-35Fe (which is no longer produced) is similar but slightly lower. The other four curves, which are for alloys with substantially higher nickel contents, reflect relatively low changes in resistance with temperature. For these alloys, rate of change reaches a peak near 540 °C (1000 °F), goes through a minimum at about 760 to 870 °C (1400 to 1600 °F), and then increases again. For Ni-Cr alloys, the change in resistance with temperature depends on section size and cooling rate. Figure 2 presents values for a typical 80Ni-20Cr alloy. The maximum change (curve A) occurs with small sections, which cool rapidly from the last production heat treatment. The smallest change occurs for heavy sections, which cool slowly. The average curve (curve B) is characteristic of medium-size sections.

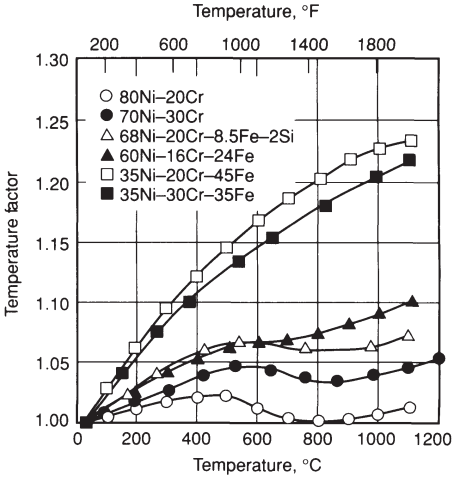


Fig. 1 Variation of resistance with temperature for six Ni-Cr and Ni-Cr-Fe alloys. To calculate resistance at temperature, multiply resistance at room temperature by the temperature factor.

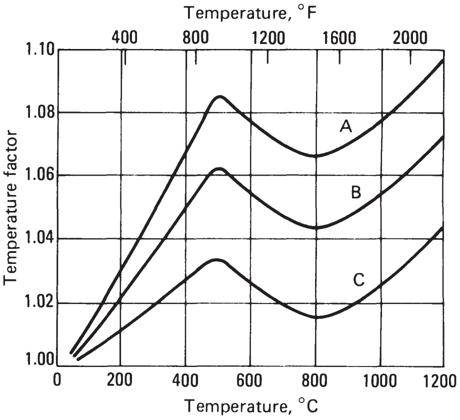


Fig. 2 Variation of resistance with temperature for 80Ni-20Cr heating alloy. Curve A is for a specimen cooled rapidly after the last production heat treatment. Curve C is for a specimen cooled slowly after the last production heat treatment. Curve B represents the average value for material as delivered by the producer. To calculate resistance at temperature, multiply the resistance at room temperature by the temperature factor.

Nickel Alloys for Resistors and Thermostats. In addition to their use as heating elements in furnaces and appliances, nickel electrical resistance alloys are also used in instruments and control equipment to measure and regulate electrical characteristics, for example, resistors, and in applications where heat generated in a metal resistor is converted to mechanical energy, for example, thermostat metals. Resistor alloys include Ni-Cr and Ni-Cr-Fe alloys similar to those used for heating elements and 75Ni-20Cr-3Al alloys containing small amounts of other metals—usually either copper, manganese, or iron. A thermostat metal is a composite material (usually in the form of sheet or strip) that consists of two or more materials bonded together, of which one may be a nonmetal. Nickel-iron, nickel-chromium-iron, and nickel-copper alloys are commonly used. Additional information on resistor and thermostat alloys can be found in the article "Electrical Resistance Alloys" in *Properties and Selection: Nonferrous Alloys and Special-Purpose Materials,* Volume 2 of the *ASM Handbook*.

Thermocouple Alloys

The thermocouple thermometer is one of the most widely used devices for measurement of temperature in the metals industry. Essentially, a thermocouple thermometer is a system consisting of a temperature-sensing element called a thermocouple, which produces an electromotive force (emf) that varies with temperature, a device for sensing emf, which may include a printed scale for converting emf to equivalent temperature units, and an electrical conductor (extension wires) for connecting the thermocouple to the sensing device. Although any combination of two dissimilar metals and/or alloys will generate a thermal emf, only eight thermocouples are in common industrial use today. These eight have been chosen on the basis of such factors as mechanical and chemical properties, stability of emf, reproducibility, and cost.

Table 3 presents base compositions, melting points, and electrical resistivities of the eight standard thermocouples. As indicated in the table, nickel-copper, nickel-chromium, nickel-silicon, and nickel alloys containing various combinations of aluminum, manganese, iron, silicon, and cobalt are used as either the positive (P) or negative (N) thermoelement. The maximum operating temperatures and limiting environmental factors for these alloys are also listed in Table 3. A nonstandard nickel-base thermocouple element consisting of 82Ni-18Mo alloy as the positive themoelement and 99Ni-1Co alloy as the negative thermoelement is also used in hydrogen or reducing atmospheres. More detailed information on thermocouple devices and materials can be found in the article "Thermocouple Materials" in *Properties and Selection: Nonferrous Alloys and Special-Purpose Materials,* Volume 2 of the *ASM Handbook* and in "Thermocouple Materials" in the *Metals Handbook Desk Edition, Second Edition*.

Nickel-Iron Soft Magnetic Alloys

Soft magnetic nickel-iron alloys containing from about 30 to 80% Ni are used extensively in applications requiring the following characteristics:

- High permeability
- High saturation magnetostriction
- Low hysteresis-energy loss
- Low eddy-current loss in alternating flux
- Low Curie temperature
- Constant permeability with changing temperature

As shown in Table 4, these include electromagnetic and radio frequency shields, transformers, amplifiers, tape recording head laminations, ground fault interrupter cores, antishoplifting devices, torque motors, and so on.

The nickel-iron alloys are generally manufactured as strip or sheet product; however, billet, bar, and wire can be produced as needed. Strip products are usually supplied in a

Table 3 Properties of standard thermocouples

Type	Thermoelements	Base composition	Melting point, °C	Resistivity, nΩ · m	Recommended service	Max temperature	
						°C	°F
J	JP	Fe	1450	100	Oxidizing or reducing	760	1400
	JN	44Ni-55Cu	1210	500			
K	KP	90Ni-9Cr	1350	700	Oxidizing	1260	2300
	KN	94Ni-Al, Mn, Fe, Si, Co	1400	320			
N	NP	84Ni-14Cr-1.4Si	1410	930	Oxidizing	1260	2300
	NN	95Ni-4.4Si-0.15 Mg	1400	370			
T	TP	OFHC Cu	1083	17	Oxidizing or reducing	370	700
	TN	44Ni-55Cu	1210	500			
E	EP	90Ni-9Cr	1350	700	Oxidizing	870	1600
	EN	44Ni-55Cu	1210	500			
R	RP	87Pt-13Rh	1860	196	Oxidizing or inert	1480	2700
	RN	Pt	1769	104			
S	SP	90Pt-10Rh	1850	189	Oxidizing or inert	1480	2700
	SN	Pt	1769	104			
B	BP	70Pt-30Rh	1927	190	Oxidizing, vacuum or inert	1700	3100
	BN	94Pt-6Rh	1826	175			

cold-rolled condition for stamping laminations or as thin foil for winding of tape toroidal cores. Strip and sheet products may also be supplied in a low-temperature, mill-annealed, fine-grain condition suitable for forming and deep drawing.

Classes of Commercial Alloys

Two broad classes of commercial alloys have been developed in the nickel-iron system. Based on nickel content, these include high-nickel alloys (about 79% Ni) and low-nickel alloys (about 45 to 50% Ni). Some alloys containing even lower nickel contents (~29 to 36%) can be used for measuring instruments requiring magnetic temperature compensation (see Table 4).

The effect of nickel content in nickel-iron alloys on saturation induction (B_s) and on initial permeability (μ_o) after annealing are illustrated in Fig. 3 and 4. Below ~28% Ni, the crystalline structure is body-centered cubic (bcc) low-carbon martensite if cooled rapidly and ferrite and austenite if cooled slowly, and these alloys are not considered useful for soft magnetic applications. Above ~28% Ni, the structure is face-centered cubic (fcc) austenite. The Curie temperature in this system is approximately room temperature at ~28% Ni and increases rapidly up to ~610 °C (1130 °F) at 68% Ni. Thus, these austenitic alloys are ferromagnetic.

The high-nickel alloys containing about 79% Ni have high initial and maximum permeabilities (Fig. 4) and very low hysteresis losses, but they also have a saturation induction of only about 0.8 T (8 kG) as shown in Fig. 3. Alloying additions of 4 to 5% Mo, or of copper and chromium to 79Ni-Fe alloys, serve to accentuate particular magnetic characteristics. Popular high-permeability alloys include the MolyPermalloys (typically 80Ni-4 to 5Mo-bal Fe) and MuMetals (typically 77Ni-5Cu-2Cr-bal Fe).

The magnetic properties of high-nickel alloys are very dependent on processing and heat treatment. Figure 5 illustrates that in ~78.5Ni-Fe, the initial permeability was low after either furnace cooling or baking at 450 °C (840 °F). However, if the same alloy was rapidly cooled from 600 °C (1110 °F), the initial permeability was increased dramatically. High-purity 78.5Ni-Fe can exhibit an initial direct current (dc) permeability of 5×10^4 and a maximum permeability of 3×10^5. These properties are obtained on ring laminations annealed in dry hydrogen at 1175 °C (2150 °F), rapid furnace cooled to room temperature, then reheated to 600 °C (1110 °F), and oil quenched. This alloy has limited commercial use because the complex heat treatment is not easily performed on parts. Also, its electrical resistivity is only 16 $\mu\Omega \cdot$ cm, which allows large eddy-current losses in alternating current (ac) applications.

High-permeability alloys must also be of high commercial purity. Air-melting and vacuum-melting practices are both used to produce low-nickel alloys, but nearly all of the high-nickel alloys are produced by vacuum induction melting (VIM). Figure 6 shows a historical perspective of the change in initial permeability of 80Ni-4Mo-Fe alloys when VIM became

Table 4 Applications for nickel-iron magnetically soft alloys

Application	Specialty alloy	Special property
Instrument transformer	79Ni-4Mo-Fe, 77Ni-5Cu-2Cr-Fe, 49Ni-Fe	High permeability, low noise and losses
Audio transformer	79Ni-4Mo-Fe, 49Ni-Fe, 45Ni-Fe, 45Ni-3Mo-Fe	High permeability, low noise and losses, transformer grade
Hearing aid transformers	79Ni-4Mo-Fe	High initial permeability, low losses
Radar pulse transformers	Oriented 49Ni-Fe, 79Ni-4Mo-Fe, 45Ni-3Mo-Fe	Processed for square hysteresis loop, tape toroidal cores
Magnetic amplifiers	Oriented 49Ni-Fe, 79Ni-4Mo-Fe	Processed for square hysteresis loop, tape toroidal cores
Transducers	45-50Ni-Fe	High saturation magnetostriction
Shielding	79Ni-4Mo-Fe, 77Ni-5Cu-2Cr-Fe, 49Ni-Fe	High permeability at low induction levels
Ground fault (GFI) interruptor core	79Ni-4Mo-Fe	High permeability, temperature stability
Sensitive direct current relays	45 to 49Ni-Fe, 78.5Ni-Fe	High permeability, low losses, low coercive force
Tape recorder head laminations	79Ni-5Mo-Fe	High permeability, low losses (0.05 to 0.03 mm, or 0.002 to 0.001 in.)
Temperature compensator	29 to 36Ni-Fe	Low Curie temperature
Dry reed magnetic switches	51Ni-Fe	Controlled expansion glass/metal sealing
Chart recorder (instrument) motors, synchronous motors	49Ni-Fe	Moderate saturation, low losses, nonoriented grade
Loading coils	81-2 brittle Moly-Permalloy	Constant permeability with changing temperature

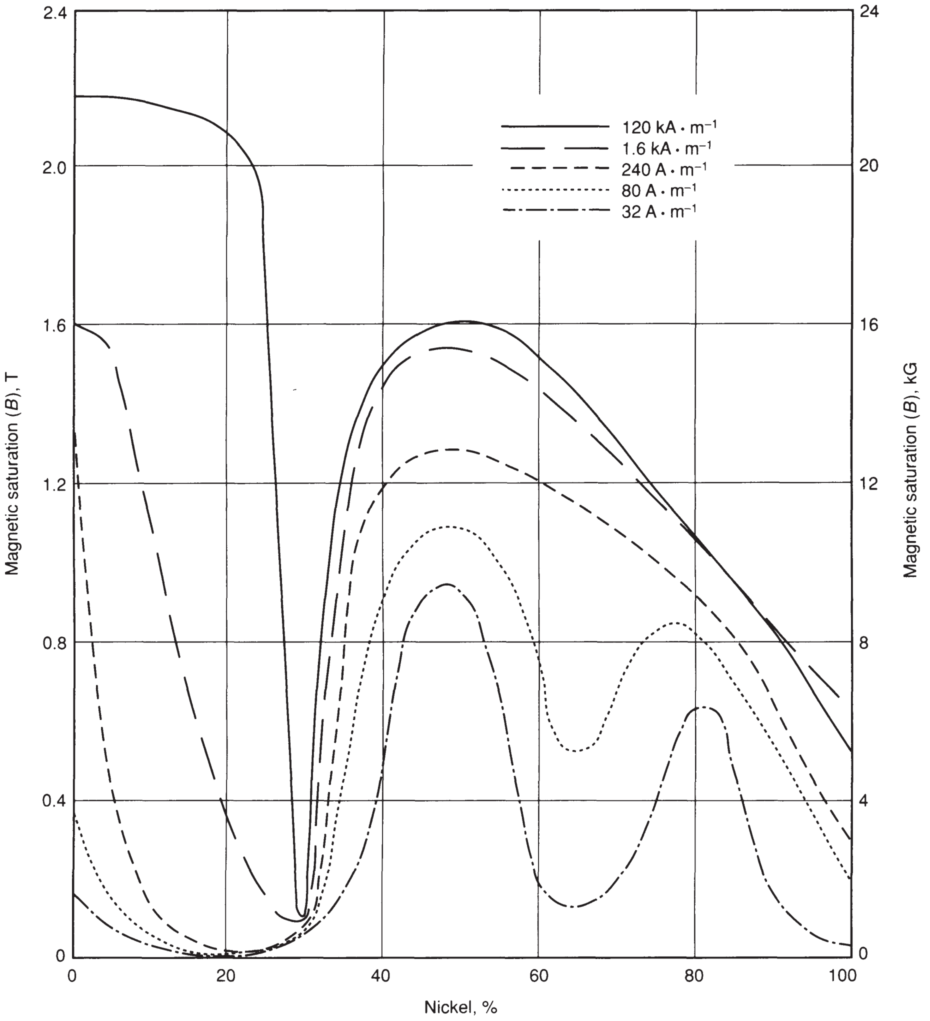


Fig. 3 Magnetic saturation of binary nickel-iron alloys at various field strengths. All samples were annealed at 1000 °C (1830 °F) and cooled in the furnace.

widely used around 1960. Interstitial impurities such as carbon, sulfur, oxygen, and nitrogen must be minimized by special melting procedures and by careful final annealing of laminations and other core configurations. Sulfur contents higher than several ppm and carbon in excess of 20 ppm are detrimental to final-annealed magnetic properties in high-nickel alloys.

Laminations or parts made from these high-nickel alloys are usually commercially annealed in pure dry hydrogen (dew point less than –50 °C, or –58 °F, at ~1000 to 1205 °C, or 1830 to 2200 °F) for several hours to eliminate stresses, to increase grain size, and to provide for alloy purification. They are cooled at any practical rate down to the critical ordering temperature range. The rate of cooling through the ordering range is typically 55 to 350 °C/h (100 to 630 °F/h), depending on the alloy being heat treated. Although the cooling rate below the ordering range is not critical, stresses due to rapid quenching must be avoided.

Vacuum furnaces may be used to anneal some high-nickel soft magnetic alloys if the application does not demand the optimum magnetic properties. However, dry hydrogen is strongly recommended for annealing nickel-iron alloys. Parts must always be thoroughly degreased to remove oils (particularly sulfur-bearing oils) prior to annealing.

The low-nickel alloys containing approximately 45 to 50% Ni are lower in initial and maximum permeability than the 79% Ni alloys (Fig. 4), but the low-nickel alloys have a higher saturation induction (about 1.5 T, or 15 kG, as shown in Fig. 3). Values of initial permeability (at a magnetic induction, *B*, or 4 mT, or 40 G) above 1.2×10^4 are typically obtained in low-nickel alloys, and values above 6×10^4 are typically obtained for 79Ni-4Mo-Fe alloys at 60 Hz using 0.36 mm (0.014 in.) thick laminations.

In alloys containing approximately 45 to 50% Ni, the effect of cooling rate on initial permeability is not great, as evidenced in Fig. 5. The typical annealing cycle to develop high permeability for these low-nickel alloys is similar to the high-nickel cycle, except that any cooling rate between ~55 °C/h (100 °F/h) and ~140 °C/h (252 °F/h) is usually suggested. A dry hydrogen atmosphere is also recommended for annealing low-nickel alloys.

Property Data. The magnetic properties of the nickel-iron soft magnetic alloys are a function of strip thickness, melting procedure, chemical analysis, and freedom from contaminants such as carbon, sulfur, and oxygen that can be picked up during melting, machining, or annealing. As described earlier, these alloys must be annealed in an inert dry hydrogen atmosphere to reduce carbon, to prevent surface oxidation during the annealing cycle, and to promote optimum magnetic properties. Tables 5 and 6 provide typical dc and ac magnetic characteristics of nickel-iron alloys. Table 7 lists recommended heat treatments and the resulting mechanical properties.

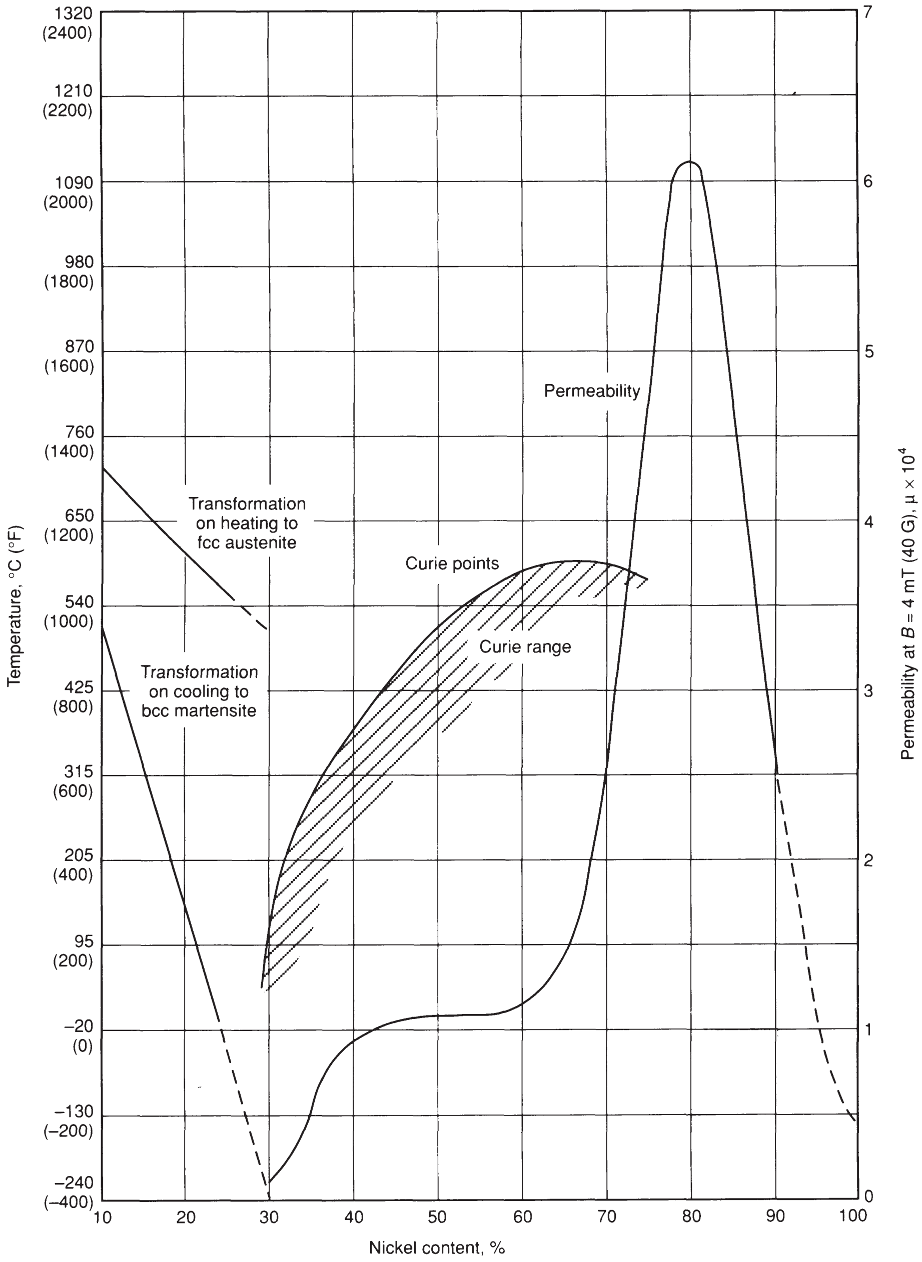


Fig. 4 Effect of nickel content on initial permeability, Curie temperature, and transformation in nickel-iron alloys

Low-Expansion Alloys

The room-temperature coefficients of thermal expansion for most metals and alloys range

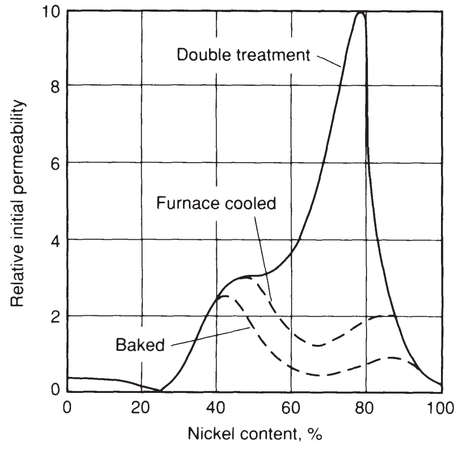


Fig. 5 Relative initial permeability at 2 mT (20 G) for Ni-Fe alloys given various heat treatments. Treatments were as follows: furnace cooled—1 h at 900 to 950 °C (1650 to 1740 °F), cooled at 100 °C/h (180 °F/h); baked—furnace cooled plus 20 h at 450 °C (840 °F); double treatment—furnace cooled plus 1 h at 600 °C (1110 °F) and cooled at 1500 °C/min (2700 °F/min).

from about 5 to 25 µm/m · K. For some applications, however, alloys must be selected that exhibit a very low thermal expansion (0 to 2 µm/m · K) or display uniform and predictable expansion over certain temperature ranges. This has resulted in a family of iron-nickel, iron-nickel-chromium, and iron-nickel-cobalt low-expansion alloys used in applications such as the following:

- Rods and tapes for geodetic surveying
- Compensating pendulums and balance wheels for clocks and watches
- Moving parts that require control of expansion, such as pistons for some internal-combustion engines
- Bimetal strip
- Glass-to-metal seals
- Thermostatic strip
- Vessels and piping for storage and transportation of liquefied natural gas
- Superconducting systems in power transmissions
- Integrated-circuit lead frames
- Components for radios and other electronic devices
- Structural components in optical and laser measuring systems

Low-expansion alloys are also used with high-expansion alloys (65%Fe-27%Ni-5%Mo, or 53%Fe-42%Ni-5%Mo) to produce movements in thermoswitches and other temperature-regulating devices.

Effect of Nickel on the Thermal Expansion of Iron

Nickel has a profound effect on the thermal expansion of iron. Depending on the nickel content, alloys of iron and nickel have coefficients of linear expansion ranging from a small negative value (–0.5 µm/m · K) to a large positive value (20 µm/m · K). Figure 7 shows the effect of nickel content on the linear expansion of iron-nickel alloys at room temperature. In the range of 30 to 60% Ni, alloys with appropriate expansion characteristics can be selected. The alloy containing 36% nickel (with small quantities of manganese, silicon, and carbon amounting to a total of less than 1%) has a coefficient of expansion so low that its length is almost invariable for ordinary changes in temperature. This alloy is known as Invar, meaning invariable.

After the discovery of Invar, an intensive study was made of the thermal and elastic properties of several similar alloys. Iron-nickel alloys that have nickel contents higher than that of Invar retain to some extent the expansion characteristics of Invar. Alloys that contain less than 36% nickel have much higher coefficients of expansion than alloys containing 36% or more nickel.

Invar (Fe-36%Ni Alloy)

Invar (UNS number K93601) and related binary iron-nickel alloys have low coefficients of expansion over only a rather narrow range of temperature (see Fig. 8). At low temperatures in the region from A to B, the coefficient of expansion is high. In the interval between B and C, the coefficient decreases, reaching a minimum in the region from C to D. With increasing temperature, the coefficient begins again to increase from D to E, and thereafter (from E to F), the expansion curve follows a trend similar to that of the nickel or iron of which the alloy is composed. The minimum expansivity prevails only in the range from C to D.

In the region between D and E in Fig. 8, the coefficient is changing rapidly to a higher value. The temperature limits for a well-annealed 36% Ni iron are 162 and 271 °C (324 and 520 °F). These temperatures correspond to the initial and final losses of magnetism in the material (that is, the Curie temperature). The slope of the curve between C and D is, then, a measure of the coefficient of expansion over a limited range of temperature.

Table 8 gives coefficients of linear expansion of iron-nickel alloys between 0 and 38 °C (32 and 100 °F). The expansion behavior of

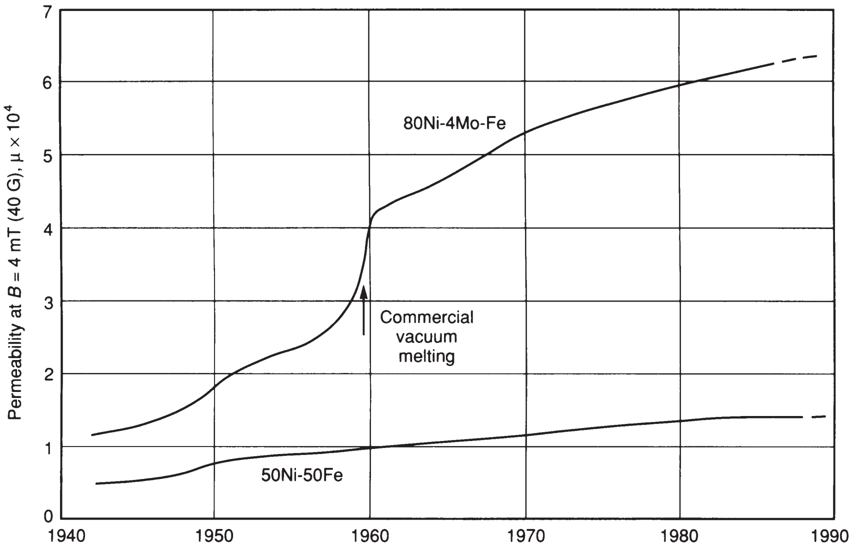


Fig. 6 Progress in initial permeability values of commercial-grade nickel-iron alloys since early 1940s. Frequency, *f*, is 60 Hz. Thickness of annealed laminations was 0.36 mm (0.014 in.).

Table 5 Typical direct current magnetic properties of annealed high-permeability nickel-iron alloys

Data for 0.30 to 1.52 mm (0.012 to 0.060 in.) thickness strip; ring laminations annealed in dry hydrogen at 1175 °C (2150 °F) (unless otherwise noted), 2 to 4 h at temperature. ASTM A 596

	Permeability		Approximate induction at maximum permeability, μ_m		Residual induction B_r		Coercive force, H_c		Saturation, induction, (B_s)		Resistivity,
Alloy	Initial × 10^3	Maximum, $\mu_m \times 10^3$	T	kG	T	kG	$A \cdot m^{-1}$	Oe	T	kG	$\mu\Omega \cdot cm$
Low nickel											
45Ni-Fe	7(a)	90	0.6	6	0.68	6.8	4	0.05	1.58	15.8	50
49Ni-Fe(b)	6.1(a)	64	0.8	8	0.96	9.6	8	0.10	1.55	15.5	47
49Ni-Fe(c)	14(a)	140	0.78	7.8	0.97	9.7	4	0.05	1.55	15.5	47
49Ni-Fe	17(a)	180	0.75	7.5	0.90	9.0	2.4	0.03	1.55	15.5	47
45Ni-3Mo-Fe	6(a)	60	0.62	6.2	0.89	8.9	4.8	0.06	1.45	14.5	65
High nickel											
78.5Ni-Fe	50(d)	300	0.35	3.5	0.50	5.0	1.0	0.013	1.05	10.5	16
79Ni-4Mo-Fe	90(d)	400	0.28	2.8	0.35	3.5	0.3	0.004	0.79	7.9	59
75Ni-5Cu-2Cr-Fe	85(d)	375	0.25	2.5	0.34	3.4	0.4	0.005	0.77	7.7	56

(a) Measured at B = 10 mT (100 G). (b) Annealed at 955 °C (1750 °F). (c) Annealed at 1065 °C (1950 °F). (d) Measured at B = 4 mT (40 G) several iron-nickel alloys over wider ranges of temperature is represented by curves 1 to 5 in Fig. 9. For comparison, Fig. 9 also includes the similar expansion obtained for ordinary steel.

Effects of Composition on Expansion Coefficient. Figure 7 shows the effect of variation in nickel content on linear expansivity. Minimum expansivity occurs at approximately 36% Ni, and small additions of other metals have considerable influences on the position of this minimum. Because further additions of nickel raise the temperature at which the inherent magnetism of the alloy disappears, the inflection temperature in the expansion curve (Fig. 8) also rises with increasing nickel content.

The addition of third and fourth elements to iron-nickel provides useful changes of desired properties (mechanical and physical) but significantly changes thermal expansion characteristics. Minimum expansivity shifts toward higher nickel contents when manganese or chromium is added and toward lower nickel contents when copper, cobalt, or carbon is added. Except for the ternary alloys with Ni-Fe-Co compositions, the value of the minimum expansivity for any of these ternary alloys is, in general, greater than that of a typical Invar alloy.

Table 6 Typical alternating current magnetic properties of annealed high-permeability nickel-iron alloys

Nominal composition	Thickness, mm (in.)	Cyclic frequency, Hz	Impedance permeability, $\mu_z \times 10^3$, at indicated induction, B(a)				
			B = 4 mT (40 G)	B = 20 mT (200 G)	B = 0.2 T (2 kG)	B = 0.4 T (4 kG)	B = 0.8 T (8 kG)
49Ni-Fe(b)	0.51 (0.020)	60	10.2	16.5	31.3	40.1	...
	0.36 (0.014)	60	12	19.4	37.3	48.2	54.7
	0.25 (0.010)	60	12	20.5	42.5	54.9	68.9
	0.15 (0.006)	60	12	21	47	63.5	85.3
	0.51 (0.020)	400	4.7	5.9	11.7	11.3	...
	0.36 (0.014)	400	6.1	7.9	14.4	17.7	13.3
	0.15 (0.006)	400	8.8	12.6	21.8	28.6	35
79Ni-4Mo-Fe	0.36 (0.014)	60	68	77	100	...	...
79Ni-5Mo-Fe	0.15 (0.006)	60	90	110	170	...	...
	0.10 (0.004)	60	110	135	230	...	...
	0.03 (0.001)	60	100	120	180	...	...
	0.36 (0.014)	400	23.2	25.4	30.5	...	...
	0.15 (0.006)	400	49.7	52.4	64.5	...	...
	0.03 (0.001)	400	89.6	105.2	180.4	...	...
49Ni-Fe(c)	0.36 (0.014)	60	...	...	...	...	...
	0.15 (0.006)	60	...	...	...	...	...
	0.36 (0.014)	400	...	...	...	...	...
	0.15 (0.006)	400	...	...	...	...	...

Nominal composition	Inductance permeability, $\mu_L \times 10^3$, DU laminations(d)				
	B = 4 mT(40 G)	B = 20 mT (200 G)	B = 0.2 T (2 kG)	B = 0.4 T (4 kG)	B = 0.8 T (8 kG)
49Ni-Fe(b)	...	...	...	...	...
	...	...	...	...	...
	...	...	...	...	...
	...	...	...	...	...
	...	...	...	...	...
	...	...	...	...	...
79Ni-4Mo-Fe	...	...	...	...	...
79Ni-5Mo-Fe	...	...	... ...	...	
	...	...	...	...	...
	...	...	...	...	...
	...	...	...	...	...
	...	...	...	...	...
	...	...	...	...	...
	...	...	...	...	...
49Ni-Fe(c)	18.6	35.8	78	110	135
	19.6	39.2	98.5	142	215
	11.8	17.6	36.4	55	30
	12.2	18.5	48.3	95	164

Nominal composition	Core loss in mW/kg (mW/lb) at indicated induction B				
	B = 4 mT (40 G)	B = 20 mT (200 G)	B = 0.2 T (2 kG)	B = 0.4 T (4 kG)	B = 0.8 T (8 kG)
49Ni-Fe(b)	...	...	...	...	...
	0.011 (0.005)	0.21 (0.097)	15 (6.7)	48 (21.7)	160 (73)
	...	...	...	...	...
	0.009 (0.004)	0.21 (0.094)	13 (5.8)	44 (19.9)	135 (62)
	...	...	...	...	...
	0.21 (0.094)	4.34 (1.97)	282 (128)	905 (410)	3880 (1760)
	0.15 (0.069)	3.20 (1.45)	238 (108)	705 (320)	2310 (1050)
79Ni-4Mo-Fe	...	0.099 (0.045)	6.50 (2.95)	...	...
79Ni-5Mo-Fe	...	0.051 (0.023)	3.00 (1.36)	...	...
	...	0.024 (0.011)	1.60 (0.73)	...	
	...	...	...	...	...
	0.11 (0.050)	2.20 (1.00)	160 (72.5)	...	...
	0.044 (0.020)	0.99 (0.45)	65.9 (29.9)	...	...
	...	...	...	...	...
49Ni-Fe(c)	0.011 (0.005)	0.22 (0.10)	15 (6.6)	51 (23)	185 (83)
	0.007 (0.003)	0.13 (0.06)	8.6 (3.9)	31 (14)	105 (47)
	0.20 (0.091)	4.4 (2.00)	306 (139)	1010 (460)	4800 (2200)
	0.11 (0.052)	2.38 (1.08)	172 (78.0)	550 (250)	1700 (790)

(a) Tested per ASTM A 772 method: thicknesses >0.13 mm (0.005 in.) tested using ring specimens; <0.13 mm (0.005 in.) tested via tape toroid specimens. (b) Nonoriented rotor or motor grade. (c) Transformer semioriented grade. (d) Per ASTM A 346 method; DU, interleaved U-shape transformer

Figure 10 shows the effects of additions of manganese, chromium, copper, and carbon. Additions of silicon, tungsten, and molybdenum produce effects similar to those caused by additions of manganese and chromium; the composition of minimum expansivity shifts toward higher contents of nickel. Addition of carbon is said to produce instability in Invar, which is attributed to the changing solubility of carbon in the austenitic matrix during heat treatment.

Effects of Processing. Heat treatment and cold work change the expansivity of Invar alloys considerably. Table 9 shows the effect of heat treatment for a 36% Ni Invar alloy. The expansivity is greatest in well-annealed material and least in quenched material.

Annealing is done at 750 to 850 °C (1380 to 1560 °F). When the alloy is quenched in water from these temperatures, expansivity is decreased, but instability is induced both in actual length and in coefficient of expansion. To overcome these deficiencies and to stabilize the material, it is common practice to stress relieve at approximately 315 to 425 °C (600 to 800 °F) and to age at a low temperature 90 °C (200 °F) for 24 to 48 hours.

Cold drawing also decreases the thermal expansion coefficient of Invar alloys. The values for the coefficients in the following table are from experiments on two heats of Invar:

Material condition	Expansivity, ppm/°C
Direct from hot mill	1.4 (heat 1) 1.4 (heat 2)
Annealed and quenched	0.5 (heat 1) 0.8 (heat 2)
Quenched and cold drawn (>70% reduction with a diameter of 3.2 to 6.4 mm, or 0.125 to 0.250 in.)	0.14 (heat 1) 0.3 (heat 2)

By cold working after quenching, it is possible to produce material with a zero, or even a negative, coefficient of expansion. A negative coefficient can be increased to zero by careful annealing at a low temperature.

Magnetic Properties. Invar and all similar iron-nickel alloys are ferromagnetic at room temperature and become paramagnetic at higher temperatures. Because additions in nickel content raise the temperature at which the inherent magnetism of the alloy disappears, the inflection temperature in the expansion curve rises with increasing nickel content. The loss of magnetism in a well-annealed sample of a true Invar begins at 162 °C (324 °F) and ends at 271 °C (520 ° F). In a quenched sample, the loss begins at 205 °C (400 °F) and ends at 271 °C (520 °F).

Table 7 Typical heat treatments and physical properties of nickel-iron alloys

Alloy nominal composition	ASTM standard	Annealing treatment(a)	Hardness	Yield Strength		Ultimate tensile strength		Elongation, %	Specific gravity
				MPa	ksi	MPa	ksi		
45Ni-Fe	A 753 Type 1	Dry hydrogen, 1120 to 1175 °C (2050 to 2150 °F), 2 to 4 h, cool at nominally 85 °C/h (150 °F/h)	48 HRB	165	24	441	64	35	8.17
49Ni-Fe	A 753 type 2	Same as 45Ni-Fe	48 HRB	165	24	441	64	35	8.25
45Ni-3Mo-Fe	...	Same as 45Ni-Fe	...	...	...	...	...	...	8.27
78.5Ni-Fe	...	Dry hydrogen, 1175 °C (2150 °F), 4 h rapid cool to RT(b), reheat to 600 °C (1110 °F), 1 h, oil quench to RT	50 HRB	159	23	455	66	35	8.60
80Ni-4Mo-Fe	A 753 type 4	Dry hydrogen, 1120 to 1175 °C (2050 to 2150 °F), 2 to 4 h cool through critical ordering temperature range, ~760 to400 °C (1400 to 750 °F) at a rate specified for the particular alloy, typically 55 °C/h (100 °F/ h) up to ~390 °C/h (700 °F/h)	58 HRB	172	25	545	79	37	8.74
80Ni-5Mo-Fe	A 753 type 4	Same as 80Ni-4Mo-Fe	58 HRB	172	25	545	79	37	8.75
77Ni-5Cu-2Cr-Fe	A 753 type 3	Same as 80Ni-4Mo-Fe	50 HRB	125	18	441	64	27	8.50

(a) All nickel-iron soft magnetic alloys should be annealed in a dry (–50 °C, or –58 °F) hydrogen atmosphere, typically for 2 to 4 h; cool as recommended by producer. Vacuum annealing generally provides lower properties, which may be acceptable depending upon specific application. (b) RT, room temperature

Table 8 Thermal expansion of iron-nickel alloys between 0 and 38 °C

Ni, %	Mean coefficient, μm/m · K
31.4	3.395 + 0.00885 *t*
34.6	1.373 + 0.00237 *t*
35.6	0.877 + 0.00127 *t*
37.3	3.457 – 0.00647 *t*
39.4	5.357 – 0.00448 *t*
43.6	7.992 – 0.00273 *t*
44.4	8.508 – 0.00251 *t*
48.7	9.901 – 0.00067 *t*
50.7	9.984 + 0.00243 *t*
53.2	10.045 + 0.00031 *t*

Table 9 Effect of heat treatment on coefficient of thermal expansion of Invar

Condition	Mean coefficient, μm/m · K
As forged	
At 17–100 °C (63–212 °F)	1.66
At 17–250 °C (63–480 °F)	3.11
Quenched from 830 °C (1530 °F)	
At 18–100 °C (65–212 °F)	0.64
At 18–250 °C (65–480 °F)	2.53
Quenched from 830 °C and tempered	
At 16–100 °C (60–212 °F)	1.02
At 16–250 °C (60–480 °F)	2.43
Quenched from 830 °C to room temperature in 19 h	
At 16–100 °C (60–212 °F)	2.01
At 16–250 °C (60–480 °F)	2.89

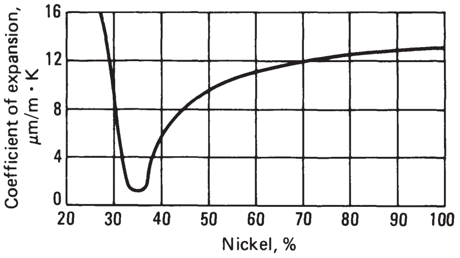


Fig. 7 Coefficient of linear expansion at 20 °C versus Ni content for Fe-Ni alloys containing 0.4% Mn and 0.1% C

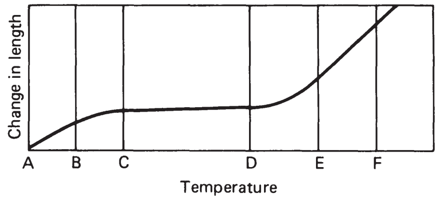


Fig. 8 Change in length of a typical Invar alloy over different ranges of temperature

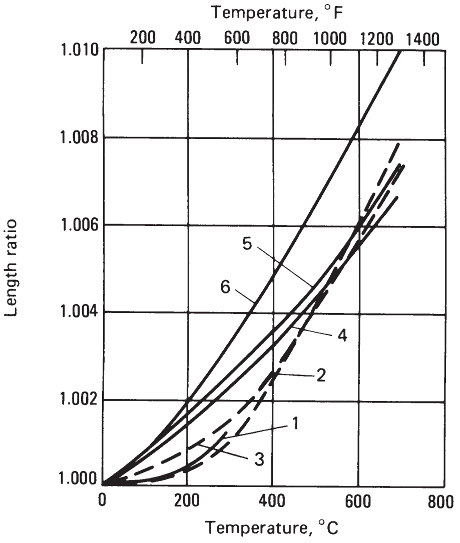


Fig. 9 Thermal expansion of iron-nickel alloys. Curve 1, 64Fe-31Ni-5Co; curve 2, 64Fe-36Ni (Invar); curve 3, 58Fe-42Ni; curve 4, 53Fe-47Ni; curve 5, 48Fe-52Ni; curve 6, carbon steel (0.25% C)

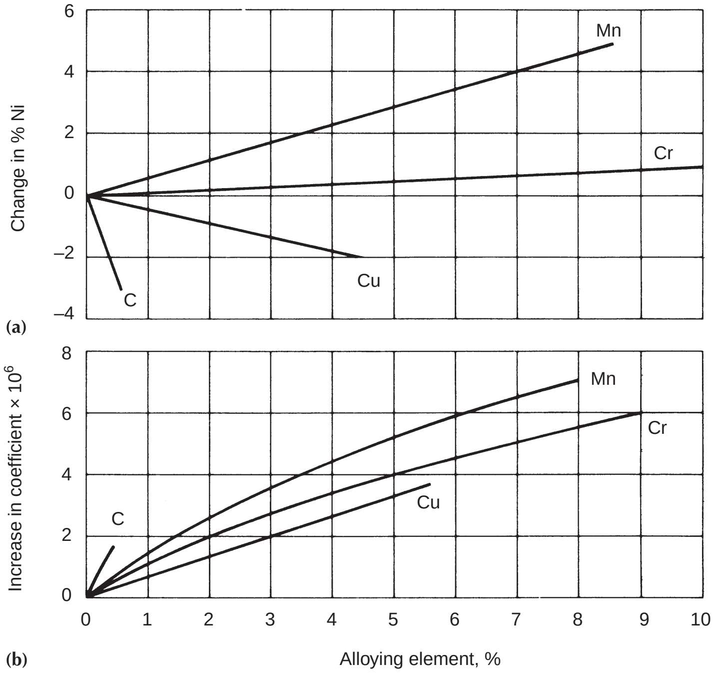


Fig. 10 Effect of alloying elements on expansion characteristics of iron-nickel alloys. (a) Displacement of nickel content caused by additions of manganese, chromium, copper, and carbon to alloy of minimum expansivity. (b) Change in value of minimum coefficient of expansion caused by additions of manganese, chromium, copper, and carbon

Electrical Properties. The electrical resistance of 36Ni-Fe Invar is between 750 and 850 nΩ · m at ordinary temperatures. The temperature coefficient of electrical resistivity is about 1.2 mΩ/Ω · K over the range of low expansivity. As nickel content increases above 36%, the electrical resistivity decreases to approximately 165 nΩ · m at approximately 80% NiFe.

Other Physical and Mechanical Properties. Table 10 presents data on miscellaneous properties of Invar in the hot-rolled and forged conditions. Figure 11 illustrates the effects of temperature on mechanical properties of forged 66Fe-34Ni.

Iron-Nickel Alloys Other Than Invar

Alloys containing less than 36% Ni include temperature compensator alloys (30 to 34% Ni). These exhibit linear changes in magnetic characteristics with temperature change. They are used as compensating shunts in metering devices and speedometers.

Table 10 Physical and mechanical properties of Invar

Solidus temperature, °C (°F)	1425 (2600)
Density, g/cm^3	8.1
Tensile strength, MPa (ksi)	450–585 (65–85)
Yield strength, MPa (ksi)	275–415 (40–60)
Elastic limit, MPa (ksi)	140–205 (20–30)
Elongation, %	30–45
Reduction in area, %	55–70
Scleroscope hardness	19
Brinell hardness	160
Modulus of elasticity, GPa (10^6 psi)	150 (21.4)
Thermoelastic coefficient, µm/m · K	500
Specific heat, at 25–100 °C (78–212 °F), J/kg · °C (Btu/lb · °F)	515 (0.123)
Thermal conductivity, at 20–100 °C (68–212 °F), W/m · K (Btu/ft · h · °F)	11 (6.4)
Thermoelectric potential (against copper), at –96 °C (–140 °F), µV/K	9.8

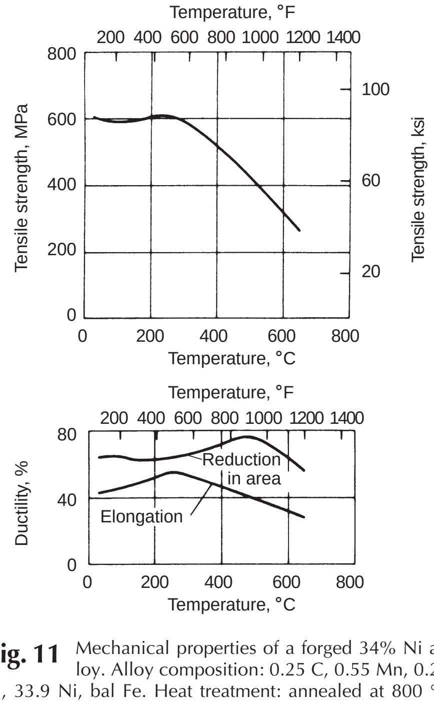


Fig. 11 Mechanical properties of a forged 34% Ni alloy. Alloy composition: 0.25 C, 0.55 Mn, 0.27 Si, 33.9 Ni, bal Fe. Heat treatment: annealed at 800 °C (1475 °F) and furnace cooled

Alloys Containing 42 to 50% Ni. Applications for these alloys include semiconductor packaging components, thermostat bimetals, glass-to-metal sealing, and glass sealing of fiber optics. Typical compositions and thermal expansion characteristics for some of these alloys are given in Table 11. Included in this group is Dumet wire, an alloy containing 42% Ni that is clad with copper to provide improved electrical conductivity and to prevent gassing at glass seals.

Iron-Nickel-Chromium Alloys

Elinvar is a low-expansion iron-nickel-chromium alloy with a thermoelastic coefficient of zero over a wide temperature range. It is more practical than the straight iron-nickel alloys with a zero thermoelastic coefficient because its thermoelastic coefficient is less susceptible to variations in nickel content expected in commercial melting.

Elinvar is used for such articles as hairsprings and balance wheels for clocks and watches and for tuning forks used in radio synchronization. Particularly beneficial where an invariable modulus of elasticity is required, it has the further advantage of being comparatively rustproof.

The composition of Elinvar has been modified somewhat from its original specification of 36% Ni and 12% Cr. The limits now used are 33 to 35 Ni, 53 to 61 Fe, 4 to 5 Cr, 1 to 3 W, 0.5 to 2 Mn, 0.5 to 2 Si, and 0.5 to 2 C. Elinvar, as created by Guillaume and Chevenard, contains 32% Ni, 10% Cr, 3.5% W, and 0.7% C.

Other iron-nickel-chromium alloys with 40 to 48% Ni and 2 to 8% Cr are useful as glass-sealing alloys because the chromium promotes improved glass-to-metal bonding as a result of its oxide-forming characteristics. The most common of these contain approximately 42 to 48% nickel with chromium of 4 to 6%.

Iron-Nickel-Cobalt Alloys

Super-Invar. Substitution of ~5% Co for some of the nickel content in the 36% Ni (Invar) alloy provides an alloy with an expansion coefficient even lower than Invar. A Super-Invar alloy with a nominal 32% Ni and 4 to 5% Co will exhibit a thermal expansion coefficient close to zero, over a relatively narrow temperature range. This alloy has been used as structural components or bases for optical and laser instruments.

Kovar (UNS K94610) is a nominal 29% Ni-17%Co-54%Fe alloy that is a well-known glass-sealing alloy suitable for sealing to hard (borosilicate) glasses. Kovar has a nominal expansion coefficient of approximately 5 ppm/°C and inflection temperature of ~450 °C (840 °F). Kovar is widely used for making hermetic seals with the harder borosilicate (Pyrex, Corning, Inc., Corning, NY) glass and ceramic materials used in power tubes, microwave tubes, transistors, and diodes, as well as in integrated circuits.

Hardenable Low-Expansion, Controlled-Expansion, and Constant-Modulus Alloys

Hardenable Low-Expansion/Constant-Modulus Alloys. Alloys that have low coefficients of expansion, and alloys with constant modulus of elasticity, can be made age hardenable by adding titanium. In low-expansion alloys, nickel content must be increased when titanium is added. The higher nickel content is required because any titanium that has not combined with the carbon in the alloy will neutralize more than twice its own weight in nickel by forming an intermetallic compound during the hardening operation.

Table 11 Composition and typical thermal expansion coefficients for common iron-nickel low-expansion alloys

Alloy	ASTM specification	Composition(a), %			
		C (max)	Mn (max)	Si (max)	Ni (nom)
42 Ni-Iron	F 30	0.02	0.5	0.25	41
46 Ni-Iron	F 30	0.02	0.5	0.25	46
48 Ni-Iron	F 30	0.02	0.5	0.25	48
52 Ni-Iron	F 30	0.02	0.5	0.25	51
42 Ni-Iron (Dumet)	F 29	0.05	1.0	0.25	42
42 Ni-Iron (Thermostat)	B 753	0.10	0.4	0.25	42

	Typical thermal expansion coefficients from room temperature to:					
	300 °C (570 °F)		400 °C (750 °F)		500 °C (930 °F)	
Alloy	ppm/°C	ppm/°F	ppm/°C	ppm/°F	ppm/°C	ppm/°F
42 Ni-Iron	4.4	2.4	6.0	3.3	7.9	4.4
46 Ni-Iron	7.5	4.2	7.5	4.2	8.5	4.7
48 Ni-Iron	8.8	4.9	8.7	4.8	9.4	5.2
52 Ni-Iron	10.1	5.6	9.9	5.5	9.9	5.5
42 Ni-Iron (Dumet)	...	...	6.6	3.7	...	…
42 Ni-Iron (Thermostat)	5.8(b)	3.2(b)	5.6(c)	3.1(c)	5.7(d)	3.15(d)

(a) Balance of iron with residual impurity limits of 0.25% max Si, 0.015% max P, 0.01% max S, 0.25% max Cr, and 0.5% max Co. (b) From room temperature to 90 °C (200 °F). (c) From room temperature to 150 °C (300 °F). (d) From room temperature to 370 °C (700 °F)

As shown in Table 12, addition of titanium raises the lowest attainable rate of expansion and raises the nickel content at which the minimum expansion occurs. Titanium also lowers the inflection temperature. Mechanical properties of alloys containing 2.4% titanium and 0.06% carbon are given in Table 13.

Table 12 Minimum coefficient of expansion in low-expansion Fe-Ni alloys containing titanium

Ti, %	Optimum Ni, %	Minimum coefficient of expansion, m/m · K
0	36.5	1.4
2	40.0	2.9
3	42.5	3.6

In alloys of the constant-modulus type containing chromium, addition of titanium allows the thermoelastic coefficients to be varied by adjustment of heat-treating schedules. The alloys in Table 14 are the three most widely used compositions. The recommended solution treatment for the alloys that contain 2.4% Ti is 950 to 1000 °C (1740 to 1830 °F) for 20 to 90 min, depending on section size. Recommended duration of aging varies from 48 h at 600 °C (1110 °F) to 3 h at 730 °C (1345 °F) for solution-treated material.

For material that has been solution treated and subsequently cold worked 50%, aging time varies from 4 h at 600 °C (1100 °F) to 1 h at 730 °C (1350 °F). Table 15 gives mechanical properties of a constant-modulus alloy containing 42% Ni, 5.4% Cr, and 2.4% Ti. Heat treatment and cold work markedly affect these properties.

Table 13 Mechanical properties of low-expansion Fe-Ni alloys containing 2.4 Ti and 0.06 C

Condition	Tensile strength		Yield strength		Elongation(a), %	Hardness, HB
	MPa	ksi	MPa	ksi		
42Ni-55.5Fe-2.4Ti-0.06C(b)						
Solution treated	620	90	275	40	32	140
Solution treated and age hardened	1140	165	825	120	14	330
Solution treated, cold rolled 50% and age hardened	1345	195	1140	165	5	385
52Ni-45.5Fe-2.4Ti-0.06C(c)						
Solution treated	585	85	240	35	27	125
Solution treated and age hardened	825	120	655	95	17	305

(a) In 50 mm (2 in.). (b) Inflection temperature, 220 °C (430 °F); minimum coefficient of expansion, 3.2 m/m ·K. (c) Inflection temperature, 440 °C (824 °F); minimum coefficient of expansion, 9.5 m/m ·K

Table 14 Thermoelastic coefficients of constant modulus Fe-Ni-Cr-Ti alloys

Composition, %				Thermoelastic coefficient, annealed condition, m/m · K	Range of possible coefficients(a), m/m · K
Ni	Cr	C	Ti		
42	5.4	0.06	2.4	0	18 to –23
42	6.0	0.06	2.4	36	54 to 13
42	6.3	0.06	2.4	–36	–18 to –60

(a) Any value in this range can be obtained by varying the heat treatment.

Table 15 Mechanical properties of constant-modulus alloy 50Fe-42Ni-5.4Cr-2.4Ti

Condition	Tensile strength		Yield strength		Elongation(a), %	Hardness, HB	Modulus of elasticity	
	MPa	ksi	MPa	ksi			GPa	10^6 psi
Solution treated	620	90	240	35	40	145	165	24
Solution treated and aged 3 h at 730 °C (1345 °F)	1240	180	795	115	18	345	185	26.5
Solution treated and cold worked 50%	930	135	895	130	6	275	175	25.5
Solution treated, cold worked 50%, and aged 1 h at 730 °C (1345 °F)	1380	200	1240	180	7	395	185	27

(a) In 50 mm (2 in.)

Table 16 Composition and thermal expansion coefficients of high-strength controlled-expansion alloys

Alloy designation	Composition, %	Coefficient of thermal expansion, from room temperature to:						Inflection temperature	
		260 °C (500 °F)		370 °C (700 °F)		415 °C (780 °F)			
		ppm/°C	ppm/°F	ppm/°C	ppm/°F	ppm/°C	ppm/°F	°C	°F
Incoloy 903 and Pyromet CTX-1	0.03 C, 0.20 Si, 37.7 Ni, 16.0 Co, 1.75 Ti, 3.0 (Nb + Ta), 1.0 Al, 0.0075 B, bal Fe	7.51	4.17	7.47	4.15	7.45	4.14	440	820
Incoloy 907 and Pyromet CTX-3	0.06 C max, 0.5 Si, 38.0 Ni, 13.0 Co, 1.5 Ti, 4.8 (Nb + Ta), 0.35 Al max, 0.012 B max, bal Fe	7.65	4.25	7.50	4.15	7.55	4.20	415	780
Incoloy 909 and Pyromet CTX-909	0.06 C max, 0.40 Si, 38.0 Ni, 14.0 Co, 1.6 Ti, 4.9 (Nb + Ta), 0.15 Al max, 0.012 B max, bal Fe	7.75	4.30	7.55	4.20	7.75	4.30	415	780

High-strength controlled-expansion superalloys are based on the iron-nickel-cobalt system. They are strengthened by the addition of the age-hardening elements niobium, titanium, and aluminum. As indicated in Table 16, these alloys exhibit both a low and constant coefficient of expansion up to about 430 °C (800 °F). They also provide high strength at temperatures up to 540 °C (1000 °F). These alloys have been used by the aerospace industry to design near net-shape components and to provide closer clearance between the tips of rotating turbine blades and retainer rings. This allows for greater power output and fuel efficiencies. These high-strength alloys also allow increased strength-to-weight ratios in engine design, resulting in weight savings. Alloy 909 (UNS N19909) offers attractive properties for rocket engine thrust chambers, ordnance hardware, springs, gage blocks, and instrumentation. Additional information on iron-nickel-cobalt controlled expansion alloys can be found in the article “Uses of Cobalt” in this Handbook.

Nickel-Titanium Shape Memory Alloys

Metallic materials that demonstrate the ability to return to some previously defined shape or size when subjected to the appropriate deformation/thermal procedure are referred to as shape memory alloys (SMA). According to the shape memory effect, an alloy that is shaped at a given temperature and then reshaped at another temperature will return to the original shape when it is brought back to the shaping temperature. The shape memory effect is associated with a martensitic transformation (see “Shape Memory Alloys,” *Properties and Selection: Nonferrous Alloys and Special-Purpose Materials,* Volume 2, *ASM Handbook,* for details).

The basis of the nickel-titanium system of SMA is the binary, equiatomic (49 to 51 at.% Ni) intermetallic compound of NiTi. This intermetallic compound is extraordinary because it has a moderate solubility range for excess nickel or titanium, as well as most other metallic elements, and it also exhibits a ductility comparable to most ordinary alloys. This solubility allows alloying with many of the elements to modify both the mechanical properties and the transformation properties of the system. Excess nickel, in amounts up to approximately 1%, is the most common alloying addition. Excess nickel strongly depresses the martensitic transformation temperature and increases the yield strength of the austenite. Other frequently used elements are iron and chromium (to lower the transformation temperature), and copper (to decrease the hysteresis and lower the deformation stress of the martensite). Because common contaminants such as oxygen and carbon can also shift the transformation temperature and degrade the mechanical properties, it is also desirable to minimize the amount of these elements.

Properties

Table 17 shows the major physical properties of the basic binary Ni-Ti system and some of the mechanical properties of the alloy in the annealed condition. Selective work hardening, which can exceed 50% reduction in some cases, and proper heat treatment can greatly improve the case with which the martensite is deformed, give an austenite with much greater strength, and create material that spontaneously moves itself both on heating and on cooling (two-way shape memory). One of the biggest challenges in using this family of alloys is in developing the proper processing procedures to yield the properties desired.

Table 17 Properties of binary nickel-titanium shape memory alloys

Properties	Property value
Melting temperatures, °C (°F)	1300 (2370)
Density, g/cm^3(lb/in.^{3})	6.45 (0.233)
Resistivity, μΩ · cm	
Austenite	~100
Martensite	~70
Thermal conductivity, W/m · °C (Btu/ft · h · °F)	
Austenite	18 (10)
Martensite	8.5 (4.9)
Corrosion resistance	Similar to 300 series stainless steel or titanium alloys
Young's modulus, GPa (10^6 psi)	
Austenite	~83 (~12)
Martensite	~28–41 (~4–6)
Yield strength, MPa (ksi)	
Austenite	195–690 (28–100)
Martensite	70–140 (10–20)
Ultimate tensile strength, MPa (ksi)	895 (130)
Transformation temperatures, °C (°F)	–200 to 110 (–325 to 230)
Hysteresis, Δ°C (Δ°F)	~30 (~55)
Latent heat of transformation, kJ/kg · atom (cal/g · atom)	167 (40)
Shape memory strain	8.5% maximum

Processing

Because of the reactivity of the titanium in these alloys, all melting of them must be done in a vacuum or an inert atmosphere. Methods such as plasma-arc melting, electron-beam melting, and vacuum-induction melting are all used commercially. After ingots are melted, standard hot-forming processes such as forging, bar rolling, and extrusion can be used for initial breakdown. The alloys react slowly with air, so hot working in air is quite successful. Most cold-working processes can also be applied to these alloys, but they work harden extremely rapidly, and frequent annealing is required. Wire drawing is probably the most widely used of the techniques, and excellent surface properties and sizes as small as 0.05 mm (0.002 in.) are made routinely.

Heat treating to impart the desired memory shape is often done at 500 to 800 °C (950 to 1450 °F), but it can be done as low as 300 to 350 °C (600 to 650 °F) if sufficient time is allowed. The SMA component may need to be restrained in the desired memory shape during the heat treatment; otherwise, it may not remain there.

Applications

Applications for NiTi alloys can be grouped into four broad categories: actuation devices, constrained recovery devices, superelastic devices, and martensitic devices.

Actuation Devices. Shape memory actuation devices utilize the shape memory effect to recover a particular shape upon heating above their transformation temperatures. Shape memory actuation devices can act without constraint to freely recover their trained shape, can be fully constrained so that they provide a force, or can be partially constrained so that they perform work. The transformation temperatures of the NiTi alloy can be adjusted to activate at precisely the required temperature. Common actuation temperatures are human body temperature and boiling water temperature. Examples of shape memory actuation devices include bloodclot filters (NiTi wire is shaped to anchor itself in a vein and catch passing clots), vascular stents to reinforce blood vessels, and coffeepot themostats.

Constrained Recovery Devices. The most successful example of constrained recovery devices is hydraulic pipe couplings. These fittings are manufactured as cylindrical sleeves slightly smaller than the metal tubing they join. Their diameters are then expanded while martensitic, and on warming to austenite, these fittings shrink in diameter and strongly hold the tube ends. The tubes prevent the coupling from fully recovering its manufactured shape, and the stresses created as the coupling attempts to do so are great enough to create a joint that, in many ways, is superior to a weld.

Superelastic devices are used for applications that demand the extraordinary flexibility of NiTi. Nickel-titanium has the ability to absorb large amounts of strain energy and release it as the applied strain is removed. The elasticity of NiTi is approximately ten times that of steel. Nickel-titanium also has excellent torqueability and kink resistance, which are important for medical guidewires. Further, superelastic NiTi alloys provide a constant force over a large strain range. This has been exploited in the field of orthodontics (arch wires) where a constant force enhances tooth movement with greater patient comfort. Eyeglass frames represent another important superelastic application.

Martensitic Devices. The martensitic phase of NiTi has some unique properties that have made it an ideal material for many applications. First, the martensitic phase transformation has excellent damping characteristics due to the energy absorption characteristics of its twinned phase structure. Second, the martensitic form of NiTi has remarkable fatigue resistance. Finally, the martensitic phase is easily deformed, yet will recover its shape on heating above its transformation temperatures. Examples of martensitic devices include vibration dampers, bendable surgical tools for open heart surgery, and highly fatigue resistant wires.

Nickel-Beryllium Alloys

Beryllium additions up to about 2 wt% in nickel promote strengthening through precipitation hardening. These alloys are distinguished by very high strength, excellent formability, and excellent resistance to fatigue, elevated temperature softening, stress relaxation, and corrosion. Wrought nickel-beryllium is available in strip, rod, and wire forms. The wrought product is used primarily as mechanical and electrical/electronic components that must exhibit good spring properties at elevated temperatures (for example, thermostats, bellows, diaphragms, burn-in connectors, and sockets).

A variety of nickel-beryllium casting alloys exhibit strengths nearly as high as those of the wrought products, and they have the advantage of excellent castability. Many of the casting alloys are used in molds and cores for glass and

Table 18 Nominal compositions of commercial nickel-beryllium alloys

		Composition, wt%			
Product form	Alloy	Be	Cr	Other	Ni
Wrought	360 (UNS N03360)	1.85–2.05	...	0.4–0.6 Ti	bal(a)
Cast	M220C (UNS N03220)	2.0	...	0.5 C	bal
Cast	41C	2.75	0.5	...	bal(b)
Cast	42C	2.75	12.0	...	bal(b)
Cast	43C	2.75	6.0	...	bal(b)
Cast	44C	2.0	0.5	...	bal(b)
Cast	46C	2.0	12.0	...	bal(b)
Cast	Master	6	...	...	bal(c)

(a) 99.4 Ni + Be + Ti + Cu min, 0.25 Cu max. (b) 0.1 C max. (c) Master alloys with 10, 25, and 50 wt% Be are also available.

polymer molding, other glass-forming tools (e.g., bottle plungers and neck rings), diamond drill bit matrices, and cast turbine parts. Some casting alloys are also used in jewelry and dental applications by virtue of their high replication of detail in the investment casting process.

Compositions of the wrought and cast nickel-beryllium alloys are shown in Table 18. Only one composition is supplied in wrought form, alloy 360 (UNS N03360), which contains 1.85 to 2.05 wt% Be, 0.4 to 0.6 wt% Ti, and a balance of nickel. The most commonly employed cast composition is alloy M220C (UNS N03220), which contains 1.80 to 2.30% Be, 0.30 to 0.50% C, and a balance of nickel. Other commercially available cast alloys include a series of ternary nickel-chromiumberyllium alloys with up to 2.75% Be and 0.5 to 12.0% Cr and a 6 wt% Be master alloy.

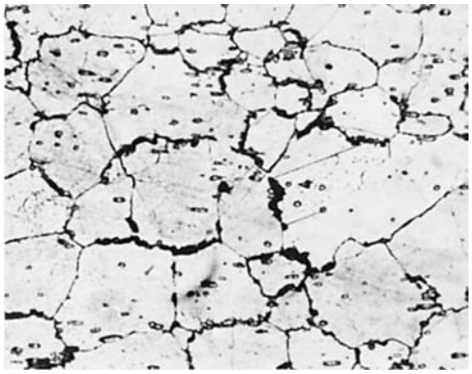


Fig. 12 Alloy 360 (UNS N03360) strip, solution annealed at 990 °C (1800 °F), water quenched, and aged at 510 °C (950 °F) for 1.5 h. The structure shows nickel-beryllium compound particles dispersed uniformly through the nickel-rich matrix. Hardening precipitates are not resolved, but equilibrium γ (NiBe) precipitates are present in grain boundaries. Modified Marble's etchant. 800×

Physical Metallurgy. The metallurgy of nickel-beryllium alloys is analogous to that of the high-strength copper-beryllium alloys. The alloys are solution annealed at a temperature high in the α-nickel region to dissolve a maximum amount of beryllium, then rapidly quenched to room temperature to create a supersaturated solid solution. Precipitation hardening involves heating the alloy to a temperature below the equilibrium solvus to nucleate and grow metastable beryllium-rich precipitates, which harden the matrix. In the high-strength copper-beryllium alloys, the equilibrium γ-precipitate forms at grain boundaries only at higher-age-hardening temperatures; commercial nickel-beryllium alloys, on the other hand, exhibit a degree of equilibrium grain-boundary precipitate formation at all temperatures in the age-hardening range.

Microstructure. Wrought unaged nickel-beryllium microstructures exhibit nickel-beryllide intermetallic compound particles containing titanium in a nickel-rich matrix of equiaxed or deformed grains, depending on whether the alloy is in the solution-annealed or a cold-worked temper. After age hardening, a small volume fraction of equilibrium nickel-beryllium phase is generally observed at the grain boundaries. In other respects, unaged and aged beryllium-nickel microstructures are essentially indistinguishable when viewed in an optical microscope. The typical microstructure of a solution annealed and aged wrought microstructure is shown in Fig. 12.

Table 19 Mechanical properties of wrought nickel-beryllium alloy 360 strip

Temper designations		Heat	Tensile strength		Yield strength at 0.2% offset		Minimum elongation	Rockwell
ASTM	Commercial	treatment(a)	MPa	ksi	MPa	ksi	in 50 mm (2 in.), %	hardness
TB00	A	...	655–895	95–130	275–485	40–70	30	39–57 HRA
TD01	¼H	...	760–1035	110–150	445–860	65–125	15	50–65 HRA
TD02	½H	...	895–1205	130–175	790–1170	115–170	4	51–70 HRA
TD04	H	...	1065–1310	154–190	1035–1310	150–190	1	55–75 HRA
TF00	AT	2.5 h at 510 °C	1480 min	215 min	1035 min	150 min	12	78–86 HRN
TH01	¼HT	2.5 h at 510 °C	1585 min	230 min	1205 min	175 min	10	80–88 HRN
TH02	½HT	1.5 h at 510 °C	1690 min	245 min	1380 min	200 min	9	81–90 HRN
TH04	HT	1.5 h at 510 °C	1860 min	270 min	1585 min	230 min	8	83–90 HRN
…	MH2	M	1065–1240	154–180	690–860	100–125	14	...
…	MH4	M	1240–1415	180–205	825–1065	120–154	12	...
…	MH6	M	1380–1550	200–225	1035–1205	150–175	10	...
…	MH8	M	1515–1690	220–245	1170–1415	170–205	9	...
…	MH10	M	1655–1860	240–270	1380–1550	200–225	8	...
…	MH12	M	1790–2000	260–290	1515–1690	20–245	8	...

(a) M, heat treatment performed at mill

Table 20 Typical mechanical properties of selected nickel-beryllium casting alloys

		Ultimate tensile strength		0.2% yield strength		Elongation in	Hardness,
Alloy	Condition	MPa	ksi	MPa	ksi	50 mm (2 in.), %	HRC
M220C	Annealed(a)	760	110	345	50	35	95
	Annealed and aged(b)	1620	235	1380	200	4	54
41C	Annealed and aged(b)	1585	230	...	...	...	55
42C	Annealed and aged(c)	1035	150	...	...	6	38
43C	Annealed and aged(b)	1310	190	...	...	...	45
44C	Annealed and aged(b)	1310	190	...	...	...	48
46C	Annealed and aged(b)	1035	150	...	...	...	35

(a) Solution annealed at 1065 °C (1950 °F) for 1 h and water quenched. (b) Solution annealed and aged at 510 °C (950 °F) for 3 h. (c) Solution annealed at 1093 °C (2000 °F) for 10 h, water quenched, and then aged at 510 °C (950 °F) for 3 h

Cast nickel-beryllium alloys containing carbon exhibit graphite nodules in a matrix of nickel-rich dendrites with an interdendritic nickel-beryllium phase. Cast chromium-containing alloys exhibit primary dendrites of nickel-chromium-beryllium solid solution and an interdendritic nickel-beryllium phase. Solution annealing cast nickel-beryllium partially spheroidizes but does not appreciably dissolve the interdendritic nickel-beryllium phase.

Heat Treatment. Wrought UNS N03360 is typically solution annealed at about 1000 °C (1830 °F). Cold work up to about 40% can be imparted between solution annealing and aging to increase the rate and magnitude of the age-hardening response. Aging to peak strength is performed at 510 °C (950 °F) for up to 2.5 h for annealed material and for up to 1.5 h for cold-worked material.

The cast binary alloys are solution annealed at about 1065 °C (1950 °F) and aged at 510 °C (950 °F) for 3 h. Cast ternary alloys are annealed at a temperature of approximately 1090 °C (1990 °F) and given the same aging treatment. Castings are typically used in the solution-annealed and aged (AT) temper for maximum strength. The cast plus aged (CT) temper is not employed.

Mechanical and Physical Properties. Annealed wrought nickel-beryllium is designated the A temper and cold worked material is designated ¼ H through H temper. As with the wrought copper-beryllium alloys, increasing cold work through about a 40% reduction in area increases the rate and magnitude of the age-hardening response. User age-hardened materials are designated the AT through HT tempers. As with the high-strength copper-beryllium alloys, nickel-beryllium strip is processed by proprietary cold-working and age-hardening techniques to provide a series of ascending-strength mill-hardened tempers designated MH2 through MH12; these tempers do not require heat treatment by the user after stamping and forming.

Mechanical properties of nickel-beryllium strip and casting alloys are given in Tables 19 and 20, respectively. The ultimate tensile strengths of wrought materials range from a minimum of 1480 MPa (215 ksi) in the annealed and aged AT temper to a minimum of 1860 MPa (270 ksi) in the cold-rolled and aged HT temper. Tensile strengths of mill-hardened strip range from 1065 MPa (155 ksi) to over 1790 MPa (260 ksi). Ductility decreases with increasing strength in both the heat-treatable and age-hardened conditions. In addition to high strength in tension, nickel-beryllium strip exhibits high fatigue strength in fully reversed bending (Fig. 13). A significant fraction of room-temperature strength is maintained through short exposure to temperatures as high as 540 °C (1000 °F).

Physical and electrical properties of selected nickel-beryllium alloys are given in Table 21. Electrical conductivity is about 6% IACS in the age-hardened condition. Nickel-beryllium displays only a fraction of the conductivity of the copper-beryllium alloys, but nickel-beryllium conductivity exceeds that of stainless steel.

Ordered Intermetallic Alloys of Ni_3Al

The ordered intermetallic compound Ni_3Al is of interest because of its excellent strength and oxidation resistance at elevated temperature. This nickel aluminide has long been used as a strengthening constituent in high-temperature nickel-base superalloys, which owe their outstanding strength properties to a fine dispersion of precipitation particles of the ordered γ′ phase (Ni_3Al) embedded in a ductile matrix (see the article "Superalloys" in this Handbook).

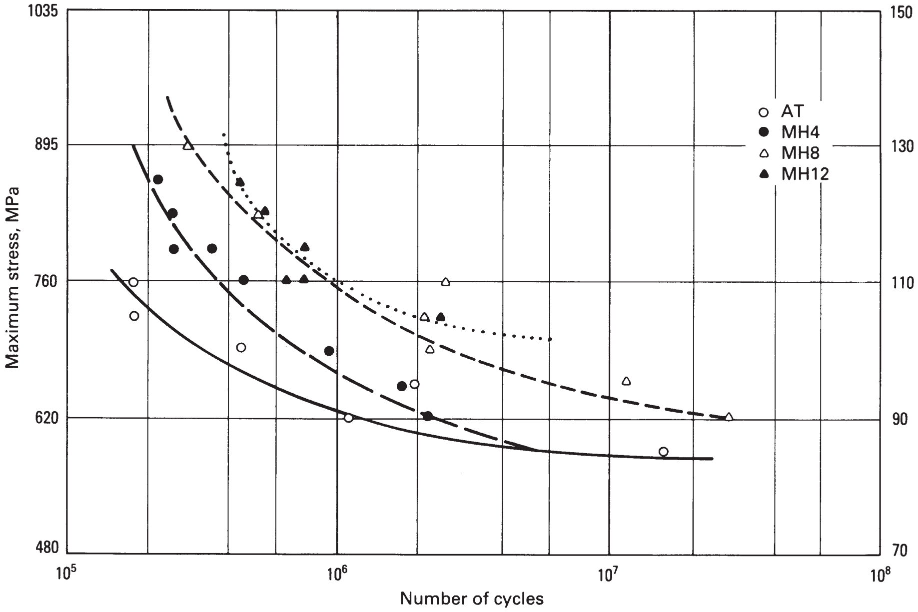


Fig. 13 Fatigue behavior of nickel-beryllium alloy N03360 strip in fully reversed bending (stress ratio, $R = -1$)

Table 21 Typical physical and electrical properties of selected nickel-beryllium alloys

Product form	Alloy	Condition	Density, g/cm^3	Thermal expansion from 20–550 °C (70–1020 °F), 10^{-6}/°C	Thermal conductivity, W/m · K	Electrical resistivity, μΩ · cm	Electrical conductivity, %IACS	Elastic modulus GPa	Elastic modulus 10^6 psi
Wrought	360 (UNS N03360)	Aged(a)	8.27	4.5	28 (at 20 °C)	28.7 max	6 min	193–206	28–30
		Mill hardened(b)	...	...	...	34.5 max	5 min	...	...
		Unaged(c)	...	...	...	43.1 max	4 min	...	...
Cast	M220C (UNS N03220)	Aged(a)	8.08–8.19	4.8	36.9 (at 38 °C) 51.1 (at 538 °C)	21.0	...	179–193	26–28
Cast	42C	Aged(a)	7.8	...	34.6 (at 93 °C)	34.5	5 min	193	28

(a) Solution annealed and aged at 510 °C (950 °F) for 3 h. (b) Heat treated by producing mill. (c) Solution annealed with 0 to 37% cold work

Table 22 Nominal compositions of selected nickel aluminide alloys

Alloy(a)	Composition, wt% Al	Cr	Fe	Zr	Mo	B	Ni
IC-50	11.3	...	...	0.6	...	0.02	bal
IC-74M	12.4	...	...	...	...	0.05	bal
IC-218	8.5	7.8	...	0.8	...	0.02	bal
IC-218 LZr	8.7	8.1	...	0.2	...	0.02	bal
IC-221	8.5	7.8	...	1.7	...	0.02	bal
IC-357	9.5	7.0	11.2	0.4	1.3	0.02	bal
IC-396M	8.0	7.7	...	0.8	3.0	0.01	bal

(a) Designations used by Oak Ridge National Laboratory, Oak Ridge, TN

Despite their great promise, the commercial success of nickel aluminides has not been achieved because of their tendency to exhibit brittle fracture and low ductility at ambient temperatures. Much of the research on these materials has centered around microalloying and macroalloying additions that would eliminate brittle behavior. The compositions, structures, and properties of alloys based on the intermetallic compound Ni_3Al are briefly outlined subsequently. More detailed information on the processing and properties of nickel aluminides can be found in the *ASM Handbook Specialty Handbook: Heat-Resistant Materials* (see the article "Structural Intermetallics").

Composition and Structure. During the latter part of the 1970s, it was found that small boron additions were critical for achieving reasonable levels of ductility in the alloys. Boron is thought to increase grain boundary cohesiveness, thereby reducing the tendency for brittle intergranular fracture. Other alloying additions were made to improve strength, castability, hot workability, and corrosion resistance. As shown in Table 22, these include chromium, iron, zirconium, and molybdenum.

Ordered nickel aluminide (Ni_3Al) alloys are based on an $L1_2$ crystal structure. The unit cell consists of an fcc arrangement in which the aluminum atoms occupy the corner positions and the nickel atoms preferentially occupy the face-centered positions. The fact that atoms occupy preferred positions in the crystal structure imparts unusual mechanical properties to the nickel aluminide alloys.

Mechanical Properties. Among the most striking properties of nickel aluminide alloys, and that which captured initial interest among metal producers, is their rising yield strength with rising temperature. Figure 14 shows that the yield strength of four nickel aluminide alloys tends to rise to a maximum in the temperature range of ~400 to 650 °C (~750 to 1200 °F). Above this temperature range, the yield strength declines. The effect of cold working on the yield strength of IC-50 alloy is shown in Fig. 15. Up to test temperatures of ~600 °C (~1110 °F), cold working had an effect on the yield strength, but at a test temperature of 800 °C (1470 °F), there was no significant enhancement of yield strength.

Corrosion Resistance. The oxidation and carburization resistance of Ni_3Al alloys are compared in Fig. 16 and 17. It is clear from Fig. 16 that the Ni_3Al alloys that form a protective Al_2O_3 scale on the surface have significantly better oxidation resistance than aluminum-free alloy 800. Carburization resistance is also high under both oxidizing or reducing environment (Fig. 17).

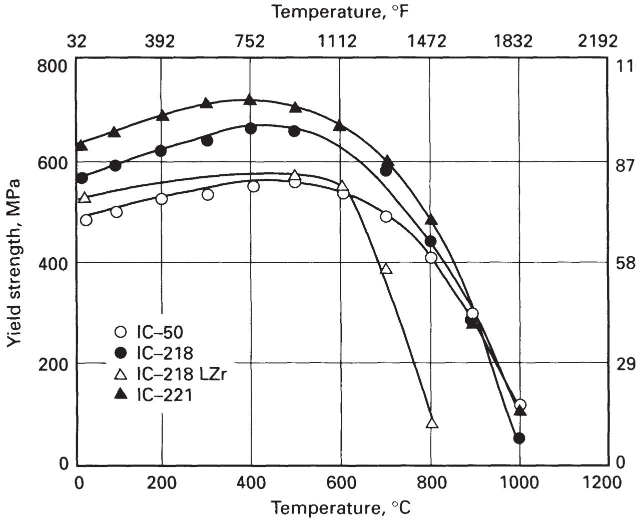


Fig. 14 Variation of yield strength with test temperature for selected nickel aluminide alloys. Strain rate, 0.5 mm/mm/min

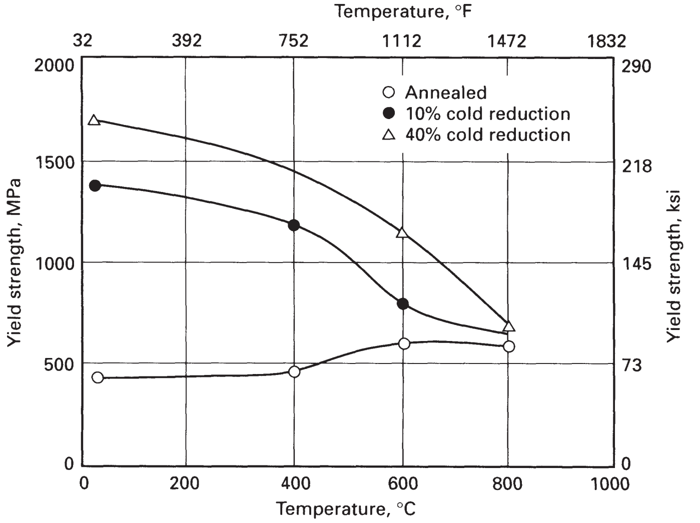


Fig. 15 Plot of yield strength versus test temperature of IC-50 nickel aluminide alloy as a function of cold working

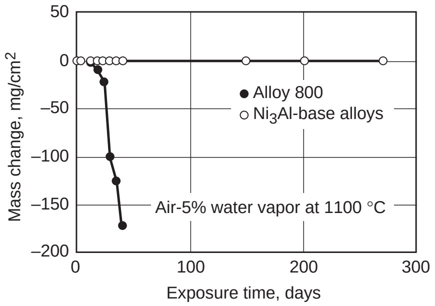
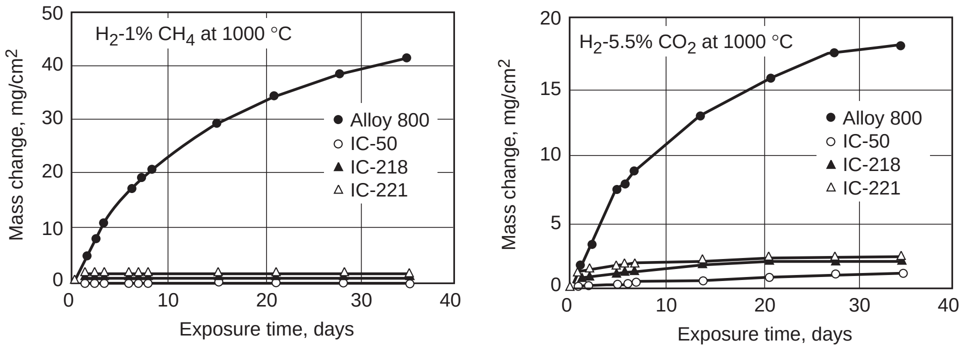


Fig. 16 Comparison of the oxidation resistance of Ni_3Al alloys with that of alloy 800 in air with 5% water vapor at 1100 °C (2010 °F)



(a)

(b)

Fig. 17 Comparison of the carburization resistance of Ni_3Al alloys with that of alloy 800. (a) Oxidizing carburizing environment. (b) Reducing carburizing environment

Applications. The potential applications (and the properties they would exploit) for nickel aluminide alloys include:

- Heat-treating furnace parts (superior carburization resistance, high-temperature strength, and thermal fatigue resistance)
- Gas, water, and steam turbines (the excellent cavitation, erosion, and oxidation resistance of the alloys)
- Aircraft fasteners (low density and ease of achieving the desired strength)
- Automotive turbochargers (high fatigue resistance and low density)
- Pistons and valves (wear resistance and capability of developing a thermal barrier by high-temperature oxidation treatment)
- Bellows for expansion joints to be used in corrosive environments (good aqueous corrosion resistance)
- Tooling (high-temperature strength and wear resistance developed through preoxidation)
- Permanent molds (the ability to develop a thermal barrier coating by high-temperature oxidation)

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- D.W. Dietrich, Magnetically Soft Materials, *Properties and Selection: Nonferrous Alloys and Special-Purpose Materials,* Vol 2, *ASM Handbook,* ASM International, 1990, p 761–781
- E.L. Frantz, Low-Expansion Alloys, *Properties and Selection: Nonferrous Alloys and Special-Purpose Materials,* Vol 2, *ASM Handbook,* ASM International, 1990, p 889–896
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- Shape Memory Alloys, *Metals Handbook Desk Edition,* 2nd ed., J.R. Davis, Ed., ASM International, 1998, p 668–669
- R.A. Watson, et al., Electrical Resistance Alloys, *Properties and Selection: Nonferrous Alloys and Special-Purpose Materials,* Vol 2, *ASM Handbook,* ASM International, 1990, p 822–839

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