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Superalloys

SUPERALLOYS are nickel-, iron-nickel-, and cobalt-base alloys generally used at temperatures above approximately 540 °C (1000 °F). They have a face-centered cubic (fcc, austenitic) structure. Iron, cobalt, and nickel are transition metals with consecutive positions in the periodic table of elements. The iron-nickel-base superalloys are an extension of stainless steel technology and generally are wrought, whereas cobalt- and nickel-base superalloys may be wrought or cast, depending on the application/composition involved.

Appropriate compositions of all superalloy-base metals can be forged, rolled to sheet, or otherwise formed into a variety of shapes. The more highly alloyed compositions normally are processed as castings. Fabricated structures can be built up by welding or brazing, but many highly alloyed compositions containing a high amount of hardening phase are difficult to weld.

Properties can be controlled by adjustments in composition and by processing (including heat treatment), and excellent elevated-temperature strengths are available in finished products. Figure 1 compares stress rupture behavior of the three alloy classes.

General Background

Important Metal Characteristics

Pure iron has a density of 7.87 g/cm^3 (0.284 lb/in.^{3}), and pure nickel and cobalt have densities of approximately 8.9 g/cm^3 (0.322 lb/in.^{3}). Iron-nickel-base superalloys have densities of approximately 7.9 to 8.3 g/cm^3 (0.285–0.300 lb/in.^{3}); cobalt-base superalloys, approximately 8.3 to 9.4 g/cm^3 (0.300–0.340 lb/in.^{3}); and nickel-base superalloys, approximately 7.8 to 8.9 g/cm^3 (0.282–0.322 lb/in.^{3}). Superalloy density is influenced by alloying additions: aluminum, titanium, and chromium reduce density, whereas tungsten, rhenium, and tantalum increase it. The corrosion resistance of superalloys depends primarily on the alloying elements added and the environment experienced.

The melting temperatures of the pure elements are as follows: nickel, 1453 °C (2647 °F); cobalt, 1495 °C (2723 °F); and iron, 1537 °C (2798 °F). Incipient melting temperatures and melting ranges of superalloys are functions of composition and prior processing. Generally, incipient melting temperatures are greater for cobalt-base than for nickel- or iron-nickel-base superalloys. Nickel-base superalloys may show incipient melting at temperatures as low as 1204 °C (2200 °F). Advanced nickel-base single-crystal superalloys with limited amounts of melting-point depressants tend to have incipient melting temperatures equal to or in excess of those of cobalt-base alloys.

Iron and cobalt both undergo allotropic transformations and become fcc at high temperatures; nickel, on the other hand, is fcc at all temperatures. In superalloys based on iron and cobalt, the fcc forms of these elements generally are stabilized by alloying additions. The upper limit of usage for superalloys is not restricted by the occurrence of allotropic transformation reactions, but rather is a function of incipient melting temperature and dissolution of strengthening phases. Some tendency toward transformation of the fcc phase to stable lower-temperature phases occasionally occurs in cobalt-base superalloys. The austenitic fcc matrices of superalloys have extended solubility for some alloying additions, excellent ductility, and favorable characteristics for precipitation of uniquely effective strengthening phases (iron-nickel- and nickel-base superalloys).

Superalloys typically have moduli of elasticity in the vicinity of 207 GPa (30 × 10^6 psi), although moduli of specific polycrystalline alloys can vary from 172 to 241 GPa (25 to 35 × 10^6 psi) at room temperature, depending on the alloy system. Processing that leads to directional grain or crystal orientation can result in moduli of approximately 124 to 310 GPa (about 18 to 45 × 10^6 psi), depending on the relation of grain or crystal orientation to testing direction. Physical properties (electrical conductivity, thermal conductivity, and thermal expansion) tend to be low compared to other metal systems. These properties are influenced by the nature of the base metals (transition elements) and the presence of refractory-metal additions.

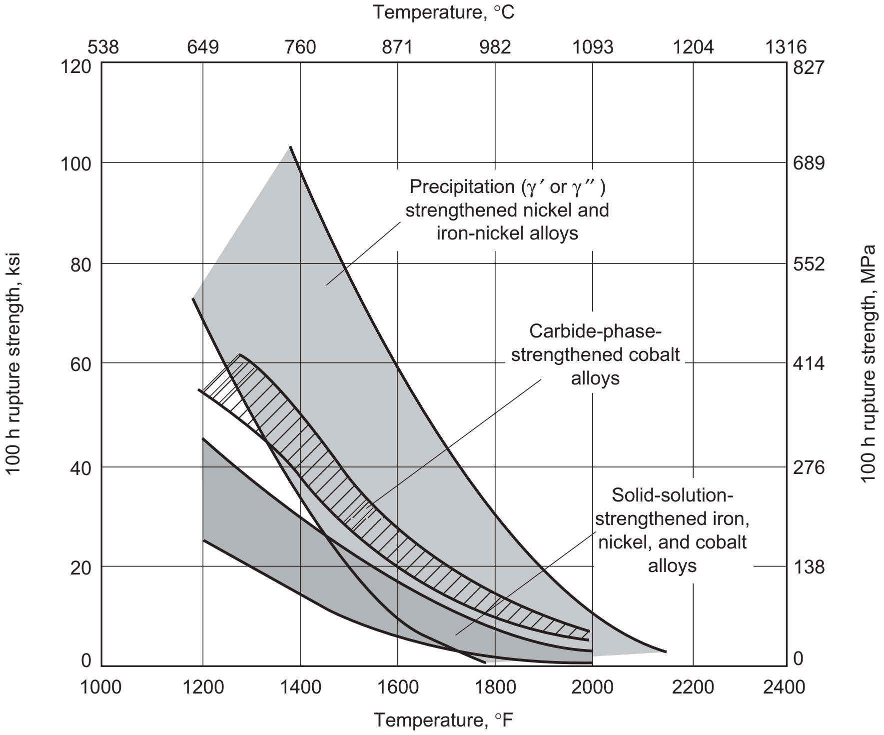


Fig. 1 General stress rutpure behavior of superalloys

The superalloys are relatively ductile, although the ductilities of cobalt-base superalloys generally are less than those of iron-nickel- and nickel-base superalloys. Iron-nickel- and nickel-base superalloys are readily available in extruded, forged, or rolled form; the higher-strength alloys generally are found only in the cast condition. Hot deformation is the preferred forming process, cold forming usually being restricted to thin sections (sheet). Cold rolling may be used to increase short-time strength properties for applications at temperatures below the lower temperature level of 540 °C (1000 °F) established in this article for superalloy use.

Phases and Structures of Superalloys

Superalloys consist of the austenitic fcc matrix phase γ plus a variety of secondary phases. Secondary phases of value in controlling properties are the carbides MC, $M_{23}C_6$, M_6C, and M_7C_3 (rare) in all superalloy types; the γ′ fcc ordered $Ni_3(Al,Ti)$, γ″ bct (body-centered tetragonal) ordered Ni_3Nb, η hexagonal ordered Ni_3Ti, and δ orthorhombic Ni_3Nb intermetallic compounds in nickel- and iron-nickel-base superalloys. The superalloys derive their strength from solid-solution hardeners and precipitated phases. Principal strengthening precipitate phases are γ′ and γ″. Carbides may provide limited strengthening directly (e.g., through dispersion hardening) or, more commonly, indirectly (e.g., by stabilizing grain boundaries against excessive shear). The δ and η phases are useful (along with γ′) in control of structure of wrought superalloys during processing. The extent to which they directly contribute to strengthening depends on the alloy and its processing.

In addition to those elements that produce solid-solution hardening and/or promote carbide and γ′ formation, other elements (e.g., boron, zirconium, and hafnium) are added to enhance mechanical or chemical properties. Some carbide- and γ′-forming elements may contribute significantly to chemical properties as well. Tables 1(a) and (b), respectively, give a generalized list of the ranges of alloying elements and their effects in superalloys. Similar information is provided in Fig. 2. Typical operating microstructures of representative superalloys are shown in Fig. 3.

Table 1(a) Common ranges of major alloying additions in superalloys

	Range, %	
Element	**Fe-Ni- and Ni-base**	**Co-base**
Chromium	5–25	19–30
Molybdenum, tungsten	0–12	0–11
Aluminum	0–6	0–4.5
Titanium	0–6	0–4
Cobalt	0–20	…
Nickel	…	0–22
Niobium	0–5	0–4
Tantalum	0–12	0–9
Rhenium	0–6	0–2

Superalloy Systems

The three types of superalloys—iron-nickel-, nickel-, and cobalt-base—may be further subdivided into cast and wrought. A large number of alloys have been invented and studied; many have been patented. However, the many alloys have been winnowed down over the years, and only a few are extensively used. Alloy usage is a function of industry (gas turbines, steam turbines, etc.). Not all alloys can be mentioned; examples of older and newer alloys are used to demonstrate the physical metallurgy response of superalloy systems. Representative superalloys and compositions emphasizing alloys developed in the United States are listed in Tables 2 to 5. Additional compositions for nickel-base superalloys can be found in the article "Powder Metallurgy Processing of Nickel Alloys" in this Handbook.

Iron-Nickel-Base. The most important class of iron-nickel-base superalloys includes those strengthened by intermetallic compound precipitation in an fcc matrix. The most common precipitate is γ′, typified by A-286, V-57, or Incoloy 901. Some alloys, typified by Inconel (IN)-718, which precipitate γ″, were formerly classed as iron-nickel-base but now are considered to be nickel-base. Other iron-nickel-base superalloys consist of modified stainless steels primarily strengthened by solid-solution hardening. Alloys in this last category vary from

Table 1(b) Role of alloying elements in superalloys

Effect(a)	Iron-base	Cobalt-base	Nickel-base
Solid-solution strengtheners	Cr, Mo	Nb, Cr, Mo, Ni, W, Ta	Co, Cr, Fe, Mo, W, Ta, Re
fcc matrix stabilizers	C, W, Ni	Ni	…
Carbide form:			
MC	Ti	Ti	W, Ta, Ti, Mo, Nb, Hf
M_7C_3	…	Cr	Cr
$M_{23}C_6$	Cr	Cr	Cr, Mo, W
M_6C	Mo	Mo, W	Mo, W, Nb
Carbonitrides: M(CN)	C, N	C, N	C, N
Promotes general precipitation of carbides	P	…	…
Forms γ′ $Ni_3(Al,Ti)$	Al, Ni, Ti	…	Al, Ti
Retards formation of hexagonal η (Ni_3Ti)	Al, Zr	…	…
Raises solvus temperature of γ′	…	…	Co
Hardening precipitates and/or intermetallics	Al, Ti, Nb	Al, Mo, Ti(b), W, Ta	Al, Ti, Nb
Oxidation resistance	Cr	Al, Cr	Al, Cr, Y, La, Ce
Improve hot corrosion resistance	La, Y	La, Y, Th	La, Th
Sulfidation resistance	Cr	Cr	Cr, Co, Si
Improves creep properties	B	…	B, Ta
Increases rupture strength	B	B, Zr	B(c)
Grain-boundary refiners	…	…	B, C, Zr, Hf
Facilitates working	…	Ni_3Ti	…
Retard γ′ coarsening	…	…	Re

(a) Not all these effects necessarily occur in a given alloy. (b) Hardening by precipitation of Ni_3Ti also occurs if sufficient Ni is present. (c) If present in large amounts, borides are formed. Source: Adapted from Ref 1

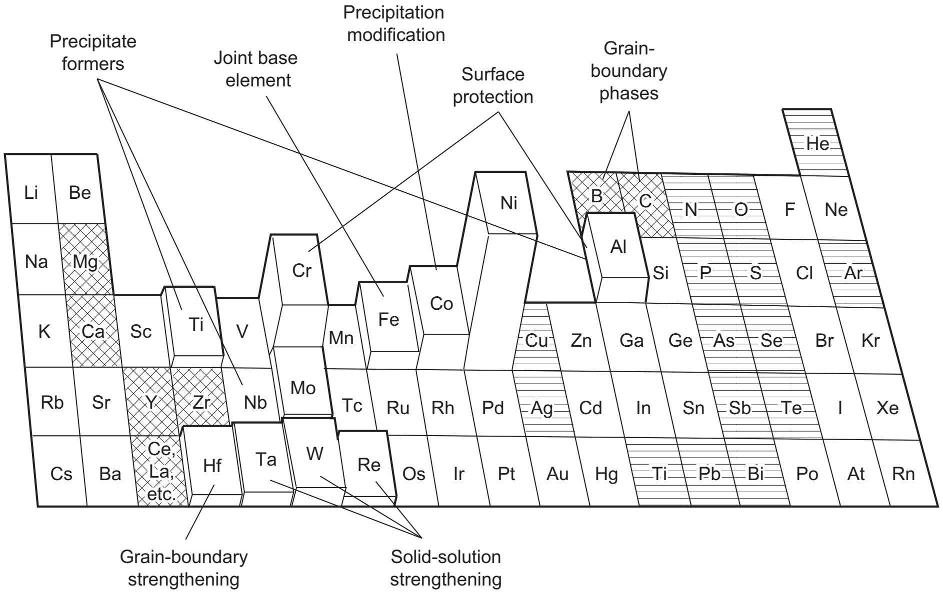


Fig. 2 Alloying elements used in nickel-base superalloys. The height of the element blocks indicates the amount that may be present. Beneficial trace elements are marked with cross hatching and harmful trace elements are marked with horizontal line hatching.

19-9DL (18-8 stainless with slight chromium and nickel adjustments, additional solution hardeners, and higher carbon) to Incoloy 800H (21 chromium, high nickel with small additions of titanium and aluminum, which yields some γ' phase).

Nickel-Base. The most important class of nickel-base superalloys is that strengthened by intermetallic-compound precipitation in an fcc matrix. For nickel-titanium/aluminum alloys the strengthening precipitate is γ'. Such alloys are typified by the wrought alloys Waspaloy and Udimet (U)-720, or by the cast alloys René 80 and IN-713. For nickel-niobium alloys the strengthening precipitate is γ''. These alloys are typified by IN-718. Some nickel-base alloys may contain both niobium plus titanium and/or aluminum and utilize both γ' and γ'' precipitates in strengthening. Alloys of this type are IN-706 and IN-909. Another class of nickel-base superalloys is essentially solid-solution strengthened. Such alloys are Hastelloy X and IN-625. The solid-solution-strengthened nickel-base alloys may derive some additional strengthening from carbide and/or intermetallic-compound precipitation. A third class includes oxide-dispersion-strengthened (ODS) alloys such as IN-MA-754 and IN-MA-6000E, which are strengthened by dispersion of inert particles such as yttria, coupled in some cases with γ' precipitation (MA-6000E).

Nickel-base superalloys are utilized in both cast and wrought forms, although special processing (powder metallurgy/isothermal forging) is frequently used to produce wrought versions of the more highly alloyed compositions

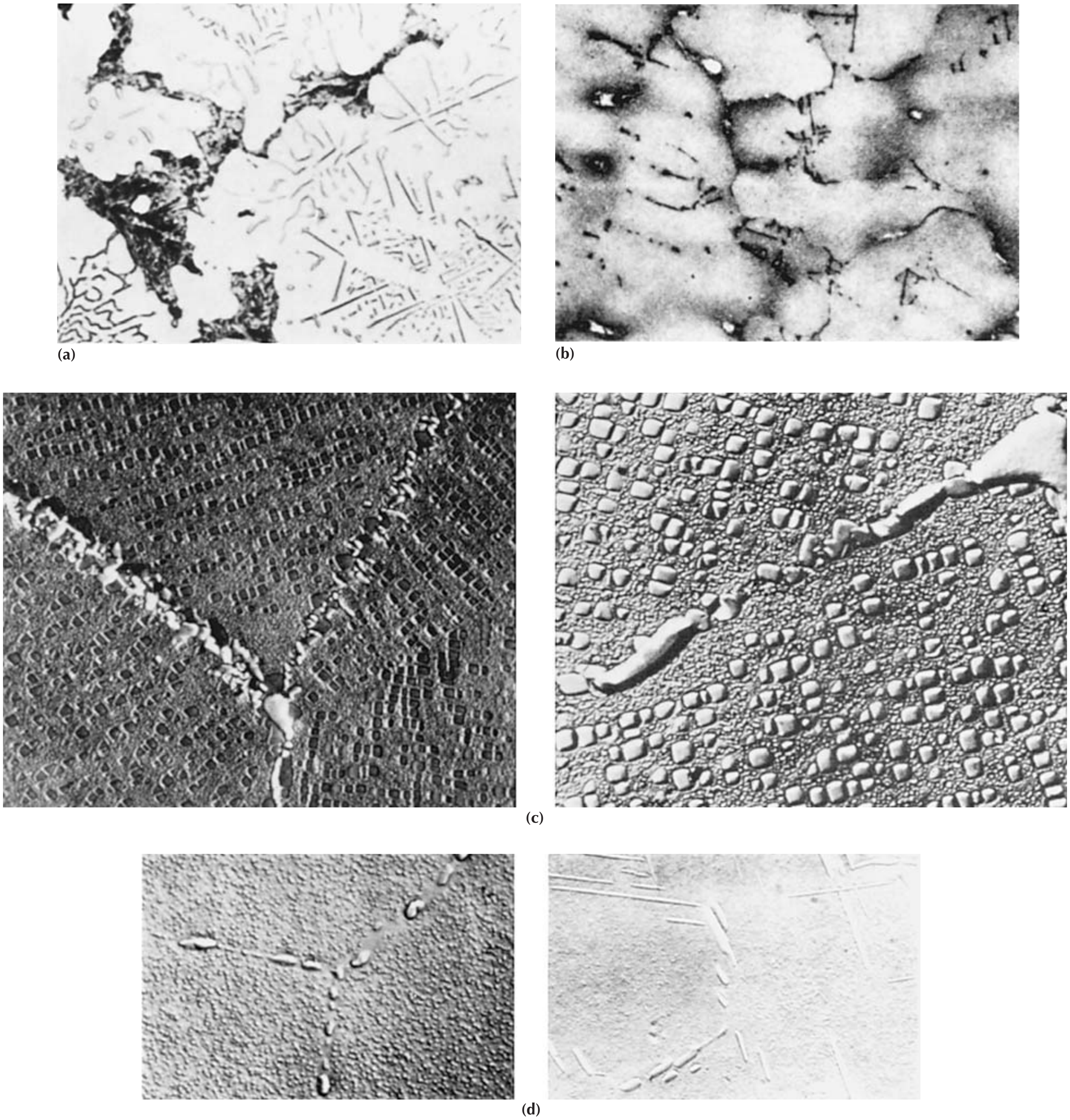


Fig. 3 Typical operating microstructures of representative superalloys. (a) Cast cobalt-base alloy. 250×. (b) Cast nickel-base alloy. 100× (c) Wrought (left, 3300×) and cast (right, 5000×) nickel-base alloys. (d) Two wrought iron-nickel-base alloys (left, 17,000×; right, 3300×). Note script carbides in (a) and (b) as well as eutectic carbide-cobalt grain-boundary structures in (a), spheroidal and cuboidal γ' as well as grain-boundary carbides in (c), and spheroidal γ' as well as grain-boundary carbides or grain-boundary and intragranular δ phase in (d). γ'' not obvious but present in (d) (right).

Table 2 Nominal compositions of wrought superalloys

Alloy	UNS No.	Composition, %										
		Cr	Ni	Co	Mo	W	Nb	Ti	Al	Fe	C	Other
Solid-solution alloys												
Iron-nickel-base												
Alloy N-155 (Multimet)	R30155	21.0	20.0	20.0	3.00	2.5	1.0	…	…	32.2	0.15	0.15 N, 0.2 La, 0.02 Zr
Haynes 556	R30556	22.0	21.0	20.0	3.0	2.5	0.1	…	0.3	29.0	0.10	0.50 Ta, 0.02 La, 0.002 Zr
19-9 DL	S63198	19.0	9.0	…	1.25	1.25	0.4	0.3	…	66.8	0.30	1.10 Mn, 0.60 Si
Incoloy 800	N08800	21.0	32.5	…	…	…	…	0.38	0.38	45.7	0.05	…
Incoloy 800H	N08810	21.0	33.0	…	…	…	…	…	…	45.8	0.08	…
Incoloy 800HT	N08811	21.0	32.5	…	…	…	…	0.4	0.4	46.0	0.08	0.8 Mn, 0.5 Si, 0.4 Cu
Incoloy 801	N08801	20.5	32.0	…	…	…	…	1.13	…	46.3	0.05	…
Incoloy 802	N08802	21.0	32.5	…	…	…	…	0.75	0.58	44.8	0.35	…
Nickel-base												
Haynes 214	N07214	16.0	76.5	…	…	…	…	…	4.5	3.0	0.03	
Haynes 230	N06230	22.0	55.0	5.0 max	2.0	14.0	…	…	0.35	3.0 max	0.10	0.015 max B, 0.02 La
Inconel 600	N06600	15.5	76.0	…	…	…	…	…	…	8.0	0.08	0.25 Cu
Inconel 601	N06601	23.0	60.5	…	…	…	…	…	1.35	14.1	0.05	0.5 Cu
Inconel 617	N06617	22.0	55.0	12.5	9.0	…	…	…	1.0	…	0.07	…
Inconel 625	N06625	21.5	61.0	…	9.0	…	3.6	0.2	0.2	2.5	0.05	…
RA 333	N06333	25.0	45.0	3.0	3.0	3.0	…	…	…	18.0	0.05	…
Hastelloy B	N10001	1.0 max	63.0	2.5 max	28.0	…	…	…	…	5.0	0.05 max	0.03 V
Hastelloy N	N10003	7.0	72.0	…	16.0	…	…	0.5 max	…	5.0 max	0.06	
Hastelloy S	N06635	15.5	67.0	…	15.5	…	…	…	0.2	1.0	0.02 max	0.02 La
Hastelloy W	N10004	5.0	61.0	2.5 max	24.5	…	…	…	…	5.5	0.12 max	0.6 V
Hastelloy X	N06002	22.0	49.0	1.5 max	9.0	0.6	…	…	2.0	15.8	0.15	…
Hastelloy C-276	N10276	15.5	59.0	…	16.0	3.7	…	…	…	5.0	0.02 max	…
Haynes HR-120	N08120	25.0	37.0	3.0	2.5	2.5	0.7	…	0.1	33.0	0.05	0.7 Mn, 0.6 Si, 0.2 N, 0.004 B
Haynes HR-160	N12160	28.0	37.0	29.0	…	…	…	…	…	2.0	0.05	2.75 Si, 0.5 Mn
Nimonic 75	N06075	19.5	75.0	…	…	…	…	0.4	0.15	2.5	0.12	0.25 max Cu
Nimonic 86	…	25.0	65.0	…	10.0	…	…	…	…	…	0.05	0.03 Ce, 0.015 Mg
Cobalt-base												
Haynes 25 (L605)	R30605	20.0	10.0	50.0	…	15.0	…	…	…	3.0	0.10	1.5 Mn
Haynes 188	R30188	22.0	22.0	37.0	…	14.5	…	…	…	3.0 max	0.10	0.90 La
Alloy S-816	R30816	20.0	20.0	42.0	4.0	4.0	4.0	…	…	4.0	0.38	…
MP35-N	R30035	20.0	35.0	35.0	10.0	…	…	…	…	…	…	…
MP159	R30159	19.0	25.0	36.0	7.0	…	0.6	3.0	0.2	9.0	…	…
Stellite B	N07718	30.0	1.0	61.5	…	4.5	…	…	…	1.0	1.0	…
UMCo-50	…	28.0	…	49.0	…	…	…	…	…	21.0	0.12	…
Precipitation-hardening alloys												
Iron-nickel-base												
A-286	S66286	15.0	26.0	…	1.25	…	…	2.0	0.2	55.2	0.04	0.005 B, 0.3 V
Discaloy	S66220	14.0	26.0	…	3.0	…	…	1.7	0.25	55.0	0.06	…
Incoloy 903	N19903	0.1 max	38.0	15.0	0.1	…	3.0	1.4	0.7	41.0	0.04	…
Pyromet CTX-1	…	0.1 max	37.7	16.0	0.1	…	3.0	1.7	1.0	39.0	0.03	…
Incoloy 907	N19907	…	38.4	13.0	…	…	4.7	1.5	0.03	42.0	0.01	0.15 Si
Incoloy 909	N19909	…	38.0	13.0	…	…	4.7	1.5	0.03	42.0	0.01	0.4 Si
Incoloy 925	N09925	20.5	44.0	…	2.8	…	…	2.1	0.2	29	0.01	1.8 Cu
V-57	…	14.8	27.0	…	1.25	…	…	3.0	0.25	48.6	0.08 max	0.01 B, 0.5 max V
W-545	S66545	13.5	26.0	…	1.5	…	…	2.85	0.2	55.8	0.08 max	0.05 B
Nickel-base												
Astroloy	N13017	15.0	56.5	15.0	5.25	…	…	3.5	4.4	<0.3	0.06	0.03 B, 0.06 Zr
Custom Age 625 PLUS	N07716	21.0	61.0	…	8.0	…	3.4	1.3	0.2	5.0	0.01	…
Haynes 242	…	8.0	62.5	2.5 max	25.0	…	…	…	0.5 max	2.0 max	0.10 max	0.006 max B
Haynes 263	N07263	20.0	52.0	…	6.0	…	…	2.4	0.6	0.7	0.06	0.6 Mn, 0.4 Si, 0.2 Cu
Haynes R-41	N07041	19.0	52.0	11.0	10.0	…	…	3.1	1.5	5.0	0.09	0.5 Si, 0.1 Mn, 0.006 B
Inconel 100	N13100	10.0	60.0	15.0	3.0	…	…	4.7	5.5	<0.6	0.15	1.0 V, 0.06 Zr, 0.015 B
Inconel 102	N06102	15.0	67.0	…	2.9	3.0	2.9	0.5	0.5	7.0	0.06	0.005 B, 0.02 Mg, 0.03 Zr
Incoloy 901	N09901	12.5	42.5	…	6.0	…	…	2.7	…	36.2	0.10 max	…
Inconel 702	N07702	15.5	79.5	…	…	…	…	0.6	3.2	1.0	0.05	0.5 Mn, 0.2 Cu, 0.4 Si
Inconel 706	N09706	16.0	41.5	…	…	…	…	1.75	0.2	37.5	0.03	2.9 (Nb + Ta), 0.15 max Cu
Inconel 718	N07718	19.0	52.5	…	3.0	…	5.1	0.9	0.5	18.5	0.08 max	0.15 max Cu
Inconel 721	N07721	16.0	71.0	…	…	…	…	3.0	…	6.5	0.04	2.2 Mn, 0.1 Cu
Inconel 722	N07722	15.5	75.0	…	…	…	…	2.4	0.7	7.0	0.04	0.5 Mn, 0.2 Cu, 0.4 Si
Inconel 725	N07725	21.0	57.0	…	8.0	…	3.5	1.5	0.35 max	9.0	0.03 max	
Inconel 751	N07751	15.5	72.5	…	…	…	1.0	2.3	1.2	7.0	0.05	0.25 max Cu
Inconel X-750	N07750	15.5	73.0	…	…	…	1.0	2.5	0.7	7.0	0.04	0.25 max Cu
M-252	N07252	19.0	56.5	10.0	10.0	…	…	2.6	1.0	<0.75	0.15	0.005 B
Nimonic 80A	N07080	19.5	73.0	1.0	…	…	…	2.25	1.4	1.5	0.05	0.10 max Cu
Nimonic 90	N07090	19.5	55.5	18.0	…	…	…	2.4	1.4	1.5	0.06	…
Nimonic 95	…	19.5	53.5	18.0	…	…	…	2.9	2.0	5.0 max	0.15 max	+B, +Zr
Nimonic 100	…	11.0	56.0	20.0	5.0	…	…	1.5	5.0	2.0 max	0.30 max	+B, +Zr
Nimonic 105	…	15.0	54.0	20.0	5.0	…	…	1.2	4.7	…	0.08	0.005 B
Nimonic 115	…	15.0	55.0	15.0	4.0	…	…	4.0	5.0	1.0	0.20	0.04 Zr

(continued)

(René 95, Astroloy, IN-100). An additional dimension of nickel-base superalloys has been the introduction of grain-aspect ratio and orientation as a means of controlling properties. In some instances, in fact, grain boundaries have been removed (see the subsequent discussion of investment casting). Wrought powder metallurgy (P/M) alloys of the ODS class and cast alloys such as MAR-M-247 have demonstrated property improvements owing to control of grain morphology by directional recrystallization or solidification.

Cobalt-Base. The cobalt-base superalloys are invariably strengthened by a combination of carbides and solid-solution hardeners. The essential distinction in these alloys is between cast and wrought structures. Cast alloys are typified by X-40 and wrought alloys by alloy

Table 2 (continued)

Alloy	UNS No.	Composition, %										
		Cr	Ni	Co	Mo	W	Nb	Ti	Al	Fe	C	Other
Precipitation-hardening alloys (continued)												
Nickel-base (continued)												
C-263	N07263	20.0	51.0	20.0	5.9	…	…	2.1	0.45	0.7 max	0.06	…
Pyromet 860	…	13.0	44.0	4.0	6.0	…	…	3.0	1.0	28.9	0.05	0.01 B
Pyromet 31	N07031	22.7	55.5	…	2.0	…	1.1	2.5	1.5	14.5	0.04	0.005 B
Refractaloy 26	…	18.0	38.0	20.0	3.2	…	…	2.6	0.2	16.0	0.03	0.015 B
René 41	N07041	19.0	55.0	11.0	10.0	…	…	3.1	1.5	<0.3	0.09	0.01 B
René 95	…	14.0	61.0	8.0	3.5	3.5	3.5	2.5	3.5	<0.3	0.16	0.01 B, 0.05 Zr
René 100	…	9.5	61.0	15.0	3.0	…	…	4.2	5.5	1.0 max	0.16	0.015 B, 0.06 Zr, 1.0 V
Udimet 500	N07500	19.0	48.0	19.0	4.0	…	…	3.0	3.0	4.0 max	0.08	0.005 B
Udimet 520	…	19.0	57.0	12.0	6.0	1.0	…	3.0	2.0	…	0.08	0.005 B
Udimet 630	…	17.0	50.0	…	3.0	3.0	6.5	1.0	0.7	18.0	0.04	0.004 B
Udimet 700	…	15.0	53.0	18.5	5.0	…	…	3.4	4.3	<1.0	0.07	0.03 B
Udimet 710	…	18.0	55.0	14.8	3.0	1.5	…	5.0	2.5	…	0.07	0.01 B
Unitemp AF2-1DA	N07012	12.0	59.0	10.0	3.0	6.0	…	3.0	4.6	<0.5	0.35	1.5 Ta, 0.015 B, 0.1 Zr
Waspaloy	N07001	19.5	57.0	13.5	4.3	…	…	3.0	1.4	2.0 max	0.07	0.006 B, 0.09 Zr

Table 3 Nominal compositions of cast polycrystalline superalloys

Alloy designation	Nominal composition, %											
	C	Ni	Cr	Co	Mo	Fe	Al	B	Ti	Ta	W	Zr	Other
Nickel-base													
Aerex 350	0.025	44.5	17	25	3	…	1.1	0.025	2.2	4	2	…	1.1 Nb
B-1900	0.1	64	8	10	6	…	6	0.015	1	4(a)	…	0.10	…
Hastelloy X	0.1	50	21	1	9	18	…	…	…	…	1	…	…
Inconel 100	0.18	60.5	10	15	3	…	5.5	0.01	5	…	…	0.06	1 V
Inconel 713C	0.12	74	12.5	…	4.2	…	6	0.012	0.8	1.75	…	0.1	0.9 Nb
Inconel 713LC	0.05	75	12	…	4.5	…	6	0.01	0.6	4	…	0.1	…
Inconel 738	0.17	61.5	16	8.5	1.75	…	3.4	0.01	3.4	…	2.6	0.1	2 Nb
Inconel 792	0.2	60	13	9	2.0	…	3.2	0.02	4.2	…	4	0.1	2 Nb
Inconel 718	0.04	53	19	…	3	18	0.5	…	0.9	…	…	…	0.1 Cu, 5 Nb
X-750	0.04	73	15	…	…	7	0.7	…	2.5	…	…	…	0.25 Cu, 0.9 Nb
M-252	0.15	56	20	10	10	…	1	0.005	2.6	…	…	…	…
MAR-M 200	0.15	59	9	10	…	1	5	0.015	2	…	12.5	0.05	1 Nb(b)
MAR-M 246	0.15	60	9	10	2.5	…	5.5	0.015	1.5	1.5	10	0.05	…
René 41	0.09	55	19	11.0	10.0	…	1.5	0.01	3.1	…	…	…	…
René 77	0.07	58	15	15	4.2	…	4.3	0.015	3.3	…	…	0.04	…
René 80	0.17	60	14	9.5	4	…	3	0.015	5	…	4	0.03	…
René 80 Hf	0.08	60	14	9.5	4	…	3	0.015	4.8	…	4	0.02	0.75 Hf
René 100	0.18	61	9.5	15	3	…	5.5	0.015	4.2	…	…	0.06	1V
René N4	0.06	62	9.8	7.5	1.5	…	4.2	0.004	3.5	4.8	6	…	0.5 Nb, 0.15 Hf
Udimet 500	0.1	53	18	17	4	2	3	…	3	…	…	…	…
Udimet 700	0.1	53.5	15	18.5	5.25	…	4.25	0.03	3.5	…	…	…	…
Udimet 710	0.13	55	18	15	3	…	2.5	…	5	…	1.5	0.08	…
Waspaloy	0.07	57.5	19.5	13.5	4.2	1	1.2	0.005	3	…	…	0.09	…
Cobalt-base													
AiResist 13	0.45	…	21	62	…	…	3.4	…	…	2	11	…	0.1 Y
AiResist 213	0.20	0.5	20	64	…	0.5	3.5	…	…	6.5	4.5	0.1	0.1 Y
AiResist 215	0.35	0.5	19	63	…	0.5	4.3	…	…	7.5	4.5	0.1	0.1 Y
FSX-414	0.25	10	29	52.5	…	1	…	0.010	…	…	7.5	…	…
Haynes 21	0.25	3	27	64	…	1	…	…	…	…	…	…	5 Mo
Haynes 25; L-605	0.1	10	20	54	…	1	…	…	…	…	15	…	…
J-1650	0.20	27	19	36	…	…	…	0.02	3.8	2	12	…	…
MAR-M 302	0.85	…	21.5	58	…	0.5	…	0.005	…	9	10	0.2	…
MAR-M 322	1.0	…	21.5	60.5	…	0.5	…	…	0.75	4.5	9	2	…
MAR-M 509	0.6	10	23.5	54.5	…	…	…	…	0.2	3.5	7	0.5	…
MAR-M 918	0.05	20	20	52	…	…	…	…	…	7.5	…	0.1	…
NASA Co-W-Re	0.40	…	3	67.5	…	…	…	…	1	…	25	1	2 Re
S-816	0.4	20	20	42	…	4	…	…	…	…	4	…	4 Mo, 4 Nb, 1.2 Mn, 0.4 Si
V-36	0.27	20	25	42	…	3	…	…	…	…	2	…	4 Mo, 2 Nb, 1 Mn, 0.4 Si
WI-52	0.45	…	21	63.5	…	2	…	…	…	…	11	…	2 Nb + Ta
X-40 (Stellite alloy 31)	0.50	10	22	57.5	…	1.5	…	…	…	…	7.5	…	0.5 Mn, 0.5 Si

(a) B-1900 + Hf also contains 1.5% Hf. (b) MAR-M 200 + Hf also contains 1.5% Hf.

25 (also known as L605). No intermetallic compound possessing the same degree of utility as the γ′ precipitate in nickel- or iron-nickel-base superalloys has been found to be operative in cobalt-base systems.

Applications

Superalloys have been used in cast, rolled, extruded, forged, and powder-processed forms. Sheet, bar, plate, tubing, shafts, airfoils, disks, and pressure vessels (cases) are some of the shapes that have been produced. These metals have been used in aircraft, industrial, and marine gas turbines; nuclear reactors; aircraft skins; spacecraft structures; petrochemical production; orthopedic and dental prostheses; and environmental protection applications. Although developed for high-temperature use, some are used at cryogenic temperatures and others at body temperature. Applications continue to expand, but at lower rates than in previous decades. Aerospace usage remains the predominant application on a volume basis.

~~Processing~~

~~*Primary and Secondary Melting*~~

~~A number of superalloys, particularly cobalt- and iron-nickel-base alloys, are air melted by various methods applicable to stainless steels. However, for most nickel- or iron-nickel-base superalloys, vacuum induction melting (VIM) is required as the primary melting process.~~

~~**Vacuum induction melting** consists of melting the required components of an alloy under high vacuum and pouring into an ingot or article mold. The use of VIM reduces interstitial gases to low levels, enables higher and more reproducible levels of aluminum and titanium (along with other relatively reactive elements) to be achieved, and results in less contamination from slag or dross formation than air melting. The benefits of reduced gas content and ability to control aluminum plus titanium are shown in Fig. 4 and 5.~~

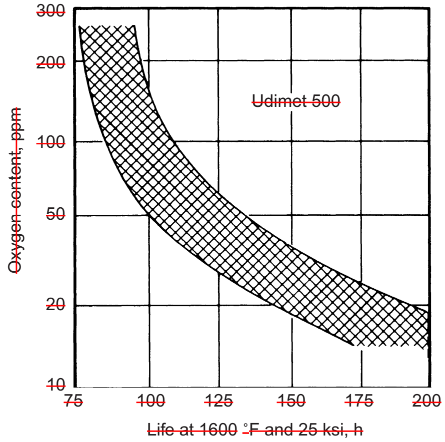
~~Segregation (on a microscale) occurs during the solidification of all superalloys. The solidification region consists of a zone where the alloy is partially solid and partially liquid (the liquid + solid zone). The solidification mode is generally dendritic and the first (primary) dendrites to form are lower in precipitate-forming elements (titanium, aluminum, niobium, and carbon) than the average melt composition. The interdendritic areas are correspondingly enriched in these solute elements. As cooling rates become slower (increasing casting size), the primary dendrites and interdendritic regions become larger. The slower the cooling rate and the more highly alloyed the melt, the larger the interdendritic regions. At some point, the interdendritic regions become large enough to interconnect and form macroscale defects. Driven by density differences between the solute-rich interdendritic liquid and the nominal melt composition, these regions become self-perpetuating continuous channels in the solidification structure. Such channel defects may grow vertically (but not truly perpendicular) from the solidification front for low-density interdendritic fluids or may grow horizontally~~

~~**Table 4** **Chemical compositions of nickel-base directionally solidified castings**~~

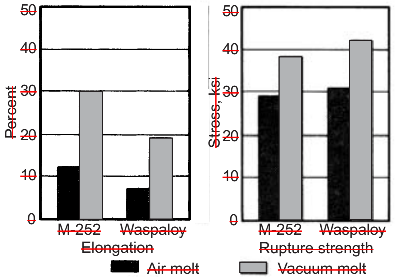
	~~Nominal composition, wt%~~													
~~Alloy~~	~~C~~	~~Cr~~	~~Co~~	~~Mo~~	~~W~~	~~Nb~~	~~Re~~	~~Ta~~	~~Al~~	~~Ti~~	~~B~~	~~Zr~~	~~Hf~~	~~Ni~~
~~**First generation**~~														
~~MAR-M 200 Hf~~	~~0.13~~	~~8.0~~	~~9.0~~	~~...~~	~~12.0~~	~~1.0~~	~~...~~	~~...~~	~~5.0~~	~~1.9~~	~~0.015~~	~~0.03~~	~~2.0~~	~~bal~~
~~René 80H~~	~~0.16~~	~~14.0~~	~~9.0~~	~~4.0~~	~~4.0~~	~~...~~	~~...~~	~~...~~	~~3.0~~	~~4.7~~	~~0.015~~	~~0.01~~	~~0.8~~	~~bal~~
~~MAR-M 002~~	~~0.15~~	~~8.0~~	~~10.0~~	~~...~~	~~10.0~~	~~...~~	~~...~~	~~2.6~~	~~5.5~~	~~1.5~~	~~0.015~~	~~0.03~~	~~1.5~~	~~bal~~
~~MAR-M 247~~	~~0.15~~	~~8.0~~	~~10.0~~	~~0.6~~	~~10.0~~	~~...~~	~~...~~	~~3.0~~	~~5.5~~	~~1.0~~	~~0.015~~	~~0.03~~	~~1.5~~	~~bal~~
~~PWA 1422~~	~~0.14~~	~~9.0~~	~~10.0~~	~~...~~	~~12.0~~	~~1.0~~	~~...~~	~~...~~	~~5.0~~	~~2.0~~	~~0.015~~	~~0.10~~	~~1.5~~	~~bal~~
~~**Second generation**~~														
~~CM 247 LC~~	~~0.07~~	~~8.0~~	~~9.0~~	~~0.5~~	~~10.0~~	~~...~~	~~...~~	~~3.2~~	~~5.6~~	~~0.7~~	~~0.015~~	~~0.010~~	~~1.4~~	~~bal~~
~~CM 186 LC~~	~~0.07~~	~~6.0~~	~~9.0~~	~~0.5~~	~~8.4~~	~~...~~	~~3.0~~	~~3.4~~	~~5.7~~	~~0.7~~	~~0.015~~	~~0.005~~	~~1.4~~	~~bal~~
~~PWA 1426~~	~~0.10~~	~~6.5~~	~~10.0~~	~~1.7~~	~~6.5~~	~~...~~	~~3.0~~	~~4.0~~	~~6.0~~	~~...~~	~~0.015~~	~~0.10~~	~~1.5~~	~~bal~~
~~René 142~~	~~0.12~~	~~6.8~~	~~12.0~~	~~1.5~~	~~4.9~~	~~...~~	~~2.8~~	~~6.35~~	~~6.15~~	~~...~~	~~0.015~~	~~0.02~~	~~1.5~~	~~bal~~

~~**Table 5** **Chemical compositions of nickel-base single-crystal castings**~~

	~~Compsition, wt%~~												
~~Alloy~~	~~Cr~~	~~Co~~	~~Mo~~	~~W~~	~~Ta~~	~~Re~~	~~V~~	~~Nb~~	~~Al~~	~~Ti~~	~~Hf~~	~~Ni~~	~~Density, g/cm^3~~
~~**First generation**~~													
~~PWA 1480~~	~~10~~	~~5~~	~~...~~	~~4~~	~~12~~	~~...~~	~~...~~	~~...~~	~~5.0~~	~~1.5~~	~~...~~	~~bal~~	~~8.70~~
~~PWA1483~~	~~12.8~~	~~9~~	~~1.9~~	~~3.8~~	~~4~~	~~...~~	~~...~~	~~...~~	~~3.6~~	~~4.0~~	~~...~~	~~bal~~	~~...~~
~~René N4~~	~~9~~	~~8~~	~~2~~	~~6~~	~~4~~	~~...~~	~~...~~	~~0.5~~	~~3.7~~	~~4.2~~	~~...~~	~~bal~~	~~8.56~~
~~SRR 99~~	~~8~~	~~5~~	~~...~~	~~10~~	~~3~~	~~...~~	~~...~~	~~...~~	~~5.5~~	~~2.2~~	~~...~~	~~bal~~	~~8.56~~
~~RR 2000~~	~~10~~	~~15~~	~~3~~	~~...~~	~~...~~	~~...~~	~~1~~	~~...~~	~~5.5~~	~~4.0~~	~~...~~	~~bal~~	~~7.87~~
~~AM1~~	~~8~~	~~6~~	~~2~~	~~6~~	~~9~~	~~...~~	~~...~~	~~...~~	~~5.2~~	~~1.2~~	~~...~~	~~bal~~	~~8.59~~
~~AM3~~	~~8~~	~~6~~	~~2~~	~~5~~	~~4~~	~~...~~	~~...~~	~~...~~	~~6.0~~	~~2.0~~	~~...~~	~~bal~~	~~8.25~~
~~CMSX-2~~	~~8~~	~~5~~	~~0.6~~	~~8~~	~~6~~	~~...~~	~~...~~	~~...~~	~~5.6~~	~~1.0~~	~~...~~	~~bal~~	~~8.56~~
~~CMSX-3~~	~~8~~	~~5~~	~~0.6~~	~~8~~	~~6~~	~~...~~	~~...~~	~~...~~	~~5.6~~	~~1.0~~	~~0.1~~	~~bal~~	~~8.56~~
~~CMSX-6~~	~~10~~	~~5~~	~~3~~	~~...~~	~~2~~	~~...~~	~~...~~	~~...~~	~~4.8~~	~~4.7~~	~~0.1~~	~~bal~~	~~7.98~~
~~CMSX-11B~~	~~12.5~~	~~7~~	~~0.5~~	~~5~~	~~5~~	~~...~~	~~...~~	~~0.1~~	~~3.6~~	~~4.2~~	~~0.04~~	~~bal~~	~~8.44~~
~~CMSX-11C~~	~~14.9~~	~~3~~	~~0.4~~	~~4.5~~	~~5~~	~~...~~	~~...~~	~~0.1~~	~~3.4~~	~~4.2~~	~~0.04~~	~~bal~~	~~8.36~~
~~AF 56 (SX 792)~~	~~12~~	~~8~~	~~2~~	~~4~~	~~5~~	~~...~~	~~...~~	~~...~~	~~3.4~~	~~4.2~~	~~...~~	~~bal~~	~~8.25~~
~~SC 16~~	~~16~~	~~...~~	~~3~~	~~...~~	~~3.5~~	~~...~~	~~...~~	~~...~~	~~3.5~~	~~3.5~~	~~...~~	~~bal~~	~~8.21~~
~~**Second generation**~~													
~~CMSX-4~~	~~6.5~~	~~9~~	~~0.6~~	~~6~~	~~6.5~~	~~3~~	~~...~~	~~...~~	~~5.6~~	~~1.0~~	~~0.1~~	~~bal~~	~~8.70~~
~~PWA 1484~~	~~5~~	~~10~~	~~2~~	~~6~~	~~9~~	~~3~~	~~...~~	~~...~~	~~5.6~~	~~...~~	~~0.1~~	~~bal~~	~~8.95~~
~~SC 180~~	~~5~~	~~10~~	~~2~~	~~5~~	~~8.5~~	~~3~~	~~...~~	~~...~~	~~5.2~~	~~1.0~~	~~0.1~~	~~bal~~	~~8.84~~
~~MC2~~	~~8~~	~~5~~	~~2~~	~~8~~	~~6~~	~~...~~	~~...~~	~~...~~	~~5.0~~	~~1.5~~	~~...~~	~~bal~~	~~8.63~~
~~René N5~~	~~7~~	~~8~~	~~2~~	~~5~~	~~7~~	~~3~~	~~...~~	~~...~~	~~6.2~~	~~...~~	~~0.2~~	~~bal~~	~~...~~
~~**Third generation**~~													
~~CMSX-10~~	~~2~~	~~3~~	~~0.4~~	~~5~~	~~8~~	~~6~~	~~...~~	~~0.1~~	~~5.7~~	~~0.2~~	~~0.03~~	~~bal~~	~~9.05~~
~~René N6~~	~~4.2~~	~~12.5~~	~~1.4~~	~~6~~	~~7.2~~	~~5.4~~	~~...~~	~~...~~	~~5.75~~	~~...~~	~~0.15~~	~~bal~~	~~8.98~~



~~**Fig. 4** Improvement of rupture life at 870 °C (1600 °F) and 170 MPa (25 ksi) by reduced oxygen content produced by vacuum melting~~



~~**Fig. 5** Effects of vacuum melting, incorporating beneficial modifications in composition, on properties of two nickel-base superalloys~~