CHAPTER **10** SELECTION OF SUPERALLOYS FOR DESIGN

Matthew J. Donachie

Rensselaer at Hartford Hartford, Connecticut

Stephen J. Donachie

Special Metals Corporation New Hartford, New York

1	INT	RODUCTION	293
	1.1	Purpose	293
	1.2	What Are Superalloys?	294
	1.3	How Are They Strengthened?	294
	1.4	Manufacture of Superalloy	
		Articles	295
	1.5	Superalloy Information	296
2	ME	TALS AT HIGH	
	TEN	MPERATURES	297
	2.1	General	297
	2.2	Mechanical Behavior	311
3	PRO	OPERTIES OF SUPERALLOYS	314
	3.1	Physical/Environmental	314
	3.2	Mechanical	316
4	EVO	DLUTION OF SUPERALLOYS	318
	4.1	Improvement of Superalloys by	
		Chemistry Control	318
5	ME	LTING AND CASTING	
	PR A	ACTICES	319
	5.1	General Aspects	319
	5.2	Melting and Refining	
		Superalloys	319
	5.3	Pros and Cons of Remelted	
		Ingot Processing	322

6	CO	MPONENT PRODUCTION	323
	6.1	Casting Practices to Produce	
		Parts	323
	6.2	Forging and Powder Metal	
		Superalloys	324
	6.3	Joining	325
	6.4	Summary of Manufacturing	
		Process	325
7	ΟΤΙ	HER ASPECTS OF	
	SUF	PERALLOY SELECTION	329
	7.1	Corrosion and Coatings for	
		Protection	329
	7.2	Special Alloys for Hot-Corrosion	
		Resistance	330
	7.3	Thermal Barrier Coatings	330
8	ALI	LOY SELECTION SUMMARY	331
	8.1	Intermediate-Temperature	
		Application	331
	8.2	High-Temperature Applications	332
9	FIN	AL COMMENTS	333
,			
	BIB	LIOGRAPHY	334

1 INTRODUCTION

1.1 Purpose

The purpose of this chapter is to provide a reasonable understanding of superalloys so that selection of them for specific designs will be appropriate. Knowl-

Handbook of Materials Selection, Edited by Myer Kutz

ISBN 0-471-35924-6 © 2002 John Wiley & Sons, Inc., New York

edge of superalloy types and their processing will give a potential user the ability to understand the ways in which superalloys can contribute to a design. More importantly, the knowledge provided here should enable the user to ask the important questions of superalloy providers to determine the necessary mechanical property and corrosion/environmental behavior that will influence alloy selection. There is no cookbook for superalloy selection. Proprietary alloys and/ or proprietary/restricted processing lead to superalloy conditions and properties not listed in a handbook or catalog of materials. With few exceptions, critical applications will require work with one or more superalloy producers to develop an understanding of what is available and what a superalloy selector/designer can expect from a chosen superalloy.

1.2 What Are Superalloys?

Superalloys for purposes of this chapter are those nickel-, iron-nickel-, and cobalt-base corrosion-resistant alloys generally used at temperatures above around 540° C (1000°F). The iron-nickel-base superalloys are an extension of stainless steel technology and generally are wrought, i.e., formed to shape or mostly to shape by hot rolling, forging, etc. The cobalt-base and nickel-base superalloys, on the other hand, may be either wrought or cast depending on the application or the alloy composition involved. The stainless steels, nickel–chromium alloys and cobalt dental alloys that evolved into the superalloys used chromium to provide elevated temperature corrosion resistance. A Cr_2O_3 layer on the surface proved very effective in protection against oxidation. Eventually, cast superalloys for the highest temperatures were protected against oxidation by chromium and aluminum. In our opinion, superalloys must contain chromium, probably at the level of 5% (some would argue 8%) or higher.

1.3 How Are They Strengthened?

Metals are crystalline and the atoms take various crystallographic forms. Some of these forms tend to be associated with better property characteristics than other crystal structures. By introducing atoms, phases, or grain boundaries, the movement of imperfections that cause deformation to occur is inhibited. The process of modifying composition and microstructure enables materials to be strengthened.

Superalloys consist of an austenitic face-centered-cubic (fcc) crystal structure matrix phase, gamma, plus a variety of secondary phases. Important secondary phases are γ' fcc ordered Ni₃(Al, Ti) and various MC, M₂₃C₆, M₆C, and M₇C₃ (rare) carbides in nickel- and iron-nickel-base superalloys. Carbides are the principal secondary phases in cobalt-base alloys. Also, γ'' , a body-centered-tetragonal (bct) phase of ordered Ni₃Nb, a hexagonal ordered Ni₃Ti (η) phase, and the δ -orthorhombic Ni₃Nb intermetallic phase can be found in nickel- and iron-nickel-base superalloys.

It is quite important for the alloy selector to have a realistic understanding of the strengthening process in superalloys as the properties of superalloys can be modified considerably by processing to manipulate the strengthening level achieved. The superalloys derive their strength from solid-solution hardeners and secondary precipitate phases that form in the γ matrix and produce precipitation (age) hardening. Principal strengthening precipitate phases in nickel-base and iron-nickel-base superalloys 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 movement). The δ - and η -phases are useful (along with γ') in control of grain structure of wrought superalloys during processing. By controlling grain structure, strength can be significantly influenced. The extent to which the second phases contribute directly to strengthening depends on the alloy and its processing. It should be noted that improper distributions of carbides and precipitate phases can be detrimental to properties.

In addition to those elements that produce solid-solution hardening and/or promote carbide and γ' formation, other elements (e.g., boron, zirconium, hafnium) are added to enhance mechanical or chemical properties. Superalloy microstructure and property control can be complex. As many as 14 elements may be controlled in some superalloys. Some carbide- and γ' -forming elements may contribute significantly to corrosion properties as well. Tables 1 and 2 give a generalized list of the ranges of alloying elements and their effects in superalloys.

1.4 Manufacture of Superalloy Articles

Appropriate compositions of all superalloys can be forged, rolled to sheet, or otherwise formed into a variety of shapes. The more highly alloyed superalloy compositions normally are processed as small castings. Large castings are made only in the weldable superalloy IN 718. Fabricated superalloy structures can be built up by welding or brazing, but the more highly alloyed the superalloy composition (i.e., higher amount of hardening phase), the more difficult it is to weld a superalloy. Machining of superalloys is similar to but more difficult than that of machining stainless steels. In welding or machining of superalloys, the effects of the energy input (heat energy, deformation energy) on the microstructure and properties of the final superalloy product must be considered.

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

	Range, (%)
Element	Fe-Ni and Ni Base	Co Base
Cr	5-25	19-30
Mo, W	0-12	0-11
Al	0–6	0-4.5
Ti	0–6	0–4
Co	0-20	
Ni	_	0-22
Nb	0–5	0–4
Та	0-12	0–9
Re	0-6	0-2

Table 1Common Ranges of Major AlloyingAdditions in Superalloys

Source: Metals Handbook Desk Edition, ASM International, Materials Park, OH 44073-0002, 1999, p. 395.

		-	
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 stabilizer	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 ₆ C	Mo	Mo, W	Mo, W, Nb
Carbonitrides: M(CN)	C, N	C, N	C, N
Promotes general precipitation of carbides	Р	_	_
Forms γ' Ni ₃ (Al,Ti)	Al, Ni, Ti	_	Al, Ti
Retards formation of hexagonal η (Ni ₃ Ti)	Al, Zr	_	_
Raises solvus temperature of γ'		—	Со
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	В	_	B, Ta
Increases rupture strength	В	B, Zr	\mathbf{B}^{c}
Grain-boundary refiners		_	B, C, Zr, Hf
Facilitates working	_	Ni ₃ Ti	_
Retard γ' coarsening	_	_	Re

Table 2 Role of Alloying Elements in Superalloys

^aNot all these effects necessarily occur in a given alloy.

^bHardening by precipitation of Ni₃Ti also occurs if sufficient Ni is prsent.

^cIf present in large amounts, borides are formed.

Source: Metals Handbook Desk Edition, ASM International, Materials Park, OH 44073-0002, 1999, p. 395.

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 about 540°C (1000°F) established in this chapter for superalloy use. Properties of superalloys generally are controlled by adjustments in chemistry (composition) and by modification of the processing (including heat treatment).

1.5 Superalloy Information

While some chemistries and properties are listed in this chapter, there is no substitute for consultation with superalloy manufacturers about the forms (cast, wrought) that can be provided and the exact chemistries available. A few producers are noted at the end of this chapter. Also, it should be understood that not all superalloys are readily available as off-the-shelf items. While literally hundreds, perhaps thousands of superalloy compositions have been evaluated since the mid-1930s, only a handful are routinely produced. Moreover, some superalloys are not available for use in all forms and sizes. Many of the highest strength alloys will only be useful as powder metal products or as castings.

Design data for superalloys are not intended to be conveyed here, but typical properties are indicated for some materials. Design properties should be obtained

from internal testing if possible or from producers or other validated sources if sufficient test data is not available inhouse. Typical properties are merely a guide for comparison. Exact chemistry, section size, heat treatment, and other processing steps must be known to generate adequate property values for design.

The properties of the extraordinary range of superalloy compositions developed over the years are not normally well documented in the literature. However, since many consumers of superalloys actually use only a few alloys, within the customary user groups, data may be more plentiful for certain compositions. The extent to which such data are available to the general public is unknown. However, even if such data were disseminated widely, the alloy selector needs to be aware that processing treatments such as forging conditions, heat treatment, coatings for corrosion protection, etc. dramatically affect properties of superalloys. All data should be reconciled with the actual manufacturing specifications and processing conditions expected. Alloy selectors should work with competent metallurgical engineers to establish the validity of data intended for design as well as to specify the processing conditions that will be used for component production.

Application of design data must take into consideration the probability of components containing locally inhomogenous regions. For wrought superalloys, the probability of occurrence of these regions (which are highly detrimental to fatigue life) is dependent upon the melting method selected (see Section 5 melting for details). For cast superalloys, the degree of inhomogeneity and the like-lihood of defects such as porosity is related to the alloy composition and the investment casting technique used to produce a component.

For sources of property data other than that of the producers (melters, forgers, etc.) or an alloy selector's own institution, one may refer to organizations, such as ASM International, that publish compilations of data that may form a basis for the development of design allowables for superalloys.

Standards organizations, such as the American Society for Testing and Materials (ASTM), publish information about superalloys but that information may not ordinarily contain any design data. The great versatility of superalloys in property modification is also a detriment to the universal compilation of property values. The same nominal alloy may have some composition modifications occur from one manufacturer or customer to another. Sometimes this extends from one country to another. Tweaking of the casting or forging process or the heat treatment, in addition to what seem like minor composition changes, can cause significant variations in properties. All facets of chemistry and processing need to be considered when selecting a superalloy for an application.

Nominal compositions of selected superalloys are provided in Table 3. Physical properties of a few superalloys are given in Tables 4 and 5, short-time (tensile) properties in Tables 6 and 7, and time-dependent (creep-rupture) properties in Tables 8 and 9. Selected reference publications for superalloy technical information or properties are indicated in the bibliography.

2 METALS AT HIGH TEMPERATURES

2.1 General

While material strengths at low temperatures are usually not a function of time, at high temperatures the time of load application becomes very significant for

Table 3 Nominal Compositions of Wrought Superalloys

	LINS							Comp	osition (%)		
Alloy	Number	Cr	Ni	Co	Мо	W	Nb	Ti	AI	Fe	С	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	_	21.0	32.5	_	_	_	_	0.75	0.58	44.8	0.35	_
Nickel-base												
Haynes 214	_	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 660	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	_	_	_		_	—	_

298

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

Toble 2	Continued	L.
iable 3	Conunuea	

	LINS	Composition (%)													
Alloy	Number	Cr	Ni	Co	Мо	W	Nb	Ti	AI	Fe	С	Other			
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			

Source: Metals Handbook Desk Edition, ASM International, Materials Park, OH 44073-0002, 1999, p. 397.

Allow	Nominal Composition (%)														
Designation	С	Ni	Cr	Co	Мо	Fe	AI	В	Ti	Та	W	Zr	Other		
Nickel Base															
B-1900	0.1	64	8	10	6	_	6	0.015	1	4^a	_	0.10	_		
CMSX-2	_	66.2	8	4.6	0.6	_	56	—	1	6	8	6	_		
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	_		
MAR-M 247	0.15	59	8.25	10	0.7	0.5	5.5	0.015	1	3	10	0.05	1.5 Hf		
PWA 1480	_	bal	10	5.0	_	_	5.0	_	1.5	12	4.0	_	_		
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	1 V		
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	_		
Waspalov	0.07	57.5	19.5	13.5	42	1	1.2	0.005	3	_		0.09	_		
WAX-20 (DS)	0.20	72				_	6.5		_	_	20	1.5	_		
Cabalt Page		. –													
AiDegist 12	0.45		21	62			2.4			2	11		0.1 Y		
AIRCSIST 15	0.43	0.5	21	64	_	0.5	3.4	_	_	4	11	0.1	0.1 1		
AiResist 215	0.20	0.5	20	62	_	0.5	3.3	_	_	0.3	4.5	0.1	0.1 1		
ESV 414	0.33	10	19	52.5	_	0.5	4.5	0.010	_	1.5	4.5	0.1	0.1 1		
F3A-414	0.25	10	29	52.5	_	1	_	0.010	_	_	7.5	_	5 M-		
Haynes 21 Haynes 25, J. 605	0.25	5 10	27	04 54	_	1	_	_	_	_	15	_	3 100		
L 1650	0.1	10	20	26	_	1	_	0.02	2.0	-	13		—		
J-1030	0.20	27	19	30 50	_	0.5	_	0.02	3.8	2	12	0.2	—		
MAR-M 302	0.85	—	21.5	58	_	0.5	_	0.005	0.75	9	10	0.2	—		
MAR-M 522	1.0	10	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	/	0.5	—		
MAR-M 918	0.05	20	20	52	_	_	—	_		7.5	25	0.1			
NASA CO-W-Ke	0.40		3	07.5	_		—	—	1	—	25	1	2 KC		
5-610	0.4	20	20	42	_	4	—	—	—	—	4	_	4 MO, 4 ND, 1.2 MI, 0.4 SI		
V-30	0.27	20	25	42	_	3	_	_	_	_	2	_	4 MO, 2 ND, 1 Mn, 0.4 Si		
W1-52	0.45	10	21	63.5	_	2	—	—	—	—	11	_	2 IND + 1a		
X-40 (Stellite alloy 31)	0.50	10	22	57.5	_	1.5	_	_	_	_	7.5	_	0.5 Mn, 0.5 Si		

Table 4 Nominal Compositions of Cast Superalloys

^{*a*}B-1900 + Hf also contains 1.5% Hf. ^{*b*}MAR-M 200 + Hf also contains 1.5% Hf.

Source: Metals Handbook Desk Edition, ASM International, Materials Park, OH 44073-0002, 1999, p. 399.

301

Table 5 Physical Properties of Cast Nickel-Base and Cobalt-Base Alloys

						Specif	ic Heat					Thermal	Conductivity					
			_	At 21°	C (70°F)	At 5 (100	38°C 00°F)	At 10 (200	093°C 00°F)	At 93	°C (200°F)	At 538	°C (1000°F)	At 1093	3°C (2000°F)	Mean Ex	Coefficient or cpansion (10	f Thermal ⁶ /K)ª
Alloy	Density (g / cm³)	°C	g Range °F	J/ kg∙K	Btu / lb ∙ °F	J/ kg ∙ K	Btu / lb ∙ °F	J/ kg∙K	Btu / lb ∙ °F	W/ m⋅K	Btu ∙ in / h ∙ ft² ∙ °F	W/ m⋅K	Btu ∙in / h ∙ft² •°F	W/ m∙K	Btu ∙in / h ∙ft² •°F	At 93°C (200°F)	At 538°C (1000°F)	At 1093°C (2000°F)
									Nickel	Base								
IN 713 C	7.01	1260	2200	420	0.10	565	0.135	710	0.17	10.0	76	17.0	118	26.4	183	10.6	12.5	17.1
IN-/13 C	7.91	1200-	2300-	420	0.10	505	0.155	/10	0.17	10.9	70	17.0	110	20.4	165	10.0	15.5	17.1
IN-713 LC	8.00	1290-	2350- 2350- 2410	440	0.105	565	0.135	710	0.17	10.7	74	16.7	116	25.3	176	10.1	15.8	18.9
B-1900	8.22	1275-	2325- 2375	_	_	_	_	_	_	(10.2)	(71)	16.3	113	_	—	11.7	13.3	16.2
Cast alloy 625	8.44			_	_	_	_	_	_	_	_	_	_	_	_	_	_	_
Cast alloy 718	8.22	1205- 1345	2200- 2450	—	—	_	—	—	—	—	—	_	—	—	—	—	—	—
IN-100	7.75	1265-	2305-	_	_	480	0.115	605	0.145	_	_	17.3	120	_	—	13.0	13.9	18.1
IN-162	8.08	1275-	2330-	_	_	_	_	_	_	_	_	_	_	_	12.2	14.1	_	
IN-731	7.75			_	_	_	_	_	_	_	_	_	_	_	_	_	_	_
IN-738	8.11	1230- 1315	2250- 2400	420	0.10	565	0.135	710	0.17	—	—	17.7	123	27.2	189	11.6	14.0	—
IN-792	8.25	_	_	_	_	_	_	_	_	_	_	_	_	_	_	_	_	_
M-22	8.63	_	_	_	_	_	_	_	_	_	_	_	_	_	_	12.4	13.3	_
MAR-M 200	8.53	1315– 1370	2400- 2500	400	0.095	420	0.10	565	0.135	13.0	90	15.2	110	29.7	206	_	13.1	17.0
MAR-M 246	8.44	1315– 1345	2400- 2450	_	_	_	—	_	_	_	_	18.9	131	30.0	208	11.3	14.8	18.6
MAR-M 247	8.53	_	_	_	_	_	_	_	_	_	_	_	_	_		_	_	_
MAR-M 421	8.08	_	_	_	_	_	_	_	_	_	_	19.1	137	32.0	229	_	14.9	19.8
MAR-M 432	8.16	_	_	_	_	_	_	_	_	_	_	_	_	_	_	_	14.9	19.3
MC-102	8.84	_	_	_	_	_	_	_	_	_	_	_	_	_	_	12.8	14.9	_
Nimocast 75	8.44	1410 ^b	2570^{b}	_	_	_	_	_	_	_	_	_	_	_	_	12.8	14.9	_
Nimocast 80	8.17	1310-	2390-	_	—	—	—	—	_	_	_	_	_	—	—	12.8	14.9	—
		1380	2515															
Nimocast 90	8.18	1310-	2390-	—	—	—	—	—	—	—	—	—	_	—	_	12.3	14.8	—
		1380	2515															
Nimocast 242	8.40	1225– 1340	2235– 2445	—	_	_	_	_	_	—	_	_	_	—	_	12.5	14.4	_
Nimocast 263	8.36	1300- 1355	2370- 2470	—	—	_	—	_	—	—	—	—	—	—	—	11.0	13.6	—
René 77	7.91	_	_	_	_	_	_	_	_	_	_	_	_	_		_	_	_
René 80	8.16	_	_	_	_	_	_	_	_	_	_	_	_	_		_	_	_
Udimet 500	8.02	1300- 1395	2375- 2540	—	—	—	—	—	—	—	_	—	_	—	—	13.3	_	_
Udimet 710	8.08	_	_	_	_	_	_	_	_	12.1	84	18.1	126	_	_	_	_	_

302

									Cobalt	Base								
FSX-414	8.3	_	_	_	_	_	_	_	_	_	_	_	_	_	_	_	_	_
Haynes 1002	8.75	1305-	2380-	420	0.10	530	0.126	645	0.154	11.0	76	21.8	151	32.1	222	12.2	14.4	—
MAP M 202	0.21	1420	2590							187	130	<u>, , , , , , , , , , , , , , , , , , , </u>	154				13.7	16.6
MAR-M 302	9.21	1313-	2500	_	_	_	_	_	_	10.7	150	22.2	154	_	_	_	15.7	10.0
MAR-M 322	8.91	1315-	2400-	—	—	_	_	_	—	—	—	—	_	—	—	—	—	—
		1360	2475															
MAR-M 509	8.85	_	_	_	_	_	_	_	_	_	_	27.9	194	44.6	310	9.8	15.9	18.2
WI-52	8.88	1300-	2425-	420	0.10	_	—	—	—	24.8	172	27.4	190	40.3	280	_	14.4	17.5
		1355	2475															
X-40	8.60	—	_	_	_	_	_	_	—	11.8	82	21.6	150	_	—	—	15.1	_

^aFrom room temperature to indicated temperature.

^bLiquidus temperature.

Source: From Advanced Materials and Processes, ASM International, Materials Park, OH 44073-0002, 2000, p. 91.

			Ulti	mate Tensile	Strength at	:			Yield	d Strength at	t 0.2% offs	et:				
		21° (70°	C F)	540 (100	°C)°F)	760 (140)°C 0°F)	21° (70)	°C °F)	540 (100)°C (0°F)	760°C (1400°F)		Tens	ile eleongatior	ı, % at:
Alloy	Form	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	21°C (70°F)	540°C (1000°F)	760°C (1400°F)
Nickel Base																
Astrolov	Bar	1415	205	1240	180	1160	168	1050	152	965	140	910	132	16	16	21
Cabot 214		915	133	715	104	560	84	560	81	510	74	495	72	38	19	9
D-979	Bar	1401	204	1295	188	720	104	1005	146	925	134	655	95	15	15	17
Hastellov C-22	Sheet	800	116	625	91	525	76	405	59	275	40	240	35	57	61	63
Hastellov G-30	Sheet	690	100	490	71		_	315	46	170	25		_	64	75	_
Hastellov S	Bar	845	130	775	112	575	84	455	65	340	49	310	45	49	50	70
Hastellov X	Sheet	785	114	650	94	435	63	360	52	290	42	260	38	43	45	37
Havnes 230	a	870	126	720	105	575	84	390	57	275	40	285	41	48	56	46
Inconel 587	Bar	1180	171	1035	150	830	120	705	102	620	90	605	88	28	22	20
Inconel 597	Bar	1220	177	1140	165	930	135	760	110	720	104	665	96	15	15	16
Inconel 600	Bar	660	96	560	81	260	38	285	41	220	32	180	26	45	41	70
Inconel 601	Sheet	740	107	725	105	200	42	455	66	350	51	220	32	40	34	78
Inconel 617	Bar	740	107	580	84	440	64	205	43	200	20	180	26	70	68	84
Inconel 617	Sheet	740	112	500	86	470	68	345	50	230	33	230	33	55	62	50
Inconel 625	Bor	065	140	010	132	550	80	400	71	415	60	415	60	50	50	15
Inconel 706	Bor	1310	140	1145	152	725	105	1005	146	910	132	660	06	20	10	32
Inconel 718	Bar	1/125	208	1275	185	050	138	1185	172	1065	154	740	107	20	19	25
Inconel 718 Direct Age	Bor	1530	200	1275	105	250	150	1365	108	1180	171	740	107	16	15	25
Inconel 718 Direct Age	Bar	1350	106	1350	170			1105	150	1020	1/1			16	10	
Inconel 718 Super	Dai	1330	190	1200	1/4		_	1105	110	725	146		_	10	10	_
M 252	Dai	1200	1/4	1030	132	045	127	813	110	745	103	720	104	16	20	10
NI-232	Dai	745	100	1230	178	943	137	040	122	200	20	160	104	10	13	10
Nimonic 75	Bar	1000	108	075	127	510	43	285	41	200	29	100	23	40	40	17
Nimonic 80A	Dai	1000	143	075	127	600	07	020	90	725	105	503	73	39	20	17
Nimonic 90	Bar	1255	179	1075	150	033	95	810	117	725	105	540	/8	35	28	12
Nimonic 105	Bar	1180	1/1	1130	164	930	135	830	120	775	112	/40	107	16	22	25
Nimonic 115	Bar	1240	180	1090	158	1085	157	803	125	195	115	800	110	27	18	24
Nimonic 263	Sneet	970	141	800	116	650	94	580	84	485	/0	460	6/	39	42	21
Nimonic 942	Bar	1405	204	1300	189	900	131	1060	154	970	141	860	125	37	26	42
Nimonic PE, 11	Bar	1080	157	1000	145	760	110	720	105	690	100	560	81	30	30	18
Nimonic PE 16	Bar	885	128	740	107	510	/4	530	11	485	70	370	54	3/	26	42
Nimonic PK 33	Sheet	1180	171	1000	145	885	128	780	113	725	105	670	97	30	30	18
Pyromet 860	Bar	1295	188	1255	182	910	132	835	121	840	122	835	121	22	15	18
René 41	Bar	1420	206	1400	203	1105	160	1060	154	1020	147	940	136	14	14	11
René 95	Bar	1620	235	1550	224	1170	170	1310	190	1255	182	1100	160	15	12	15
Udimet 400	Bar	1310	190	1185	172	—	_	930	135	830	120	—	_	30	26	_
Udimet 500	Bar	1310	190	1240	180	1040	151	840	122	795	115	730	106	32	28	39
Udimet 520	Bar	1310	190	1240	180	725	105	860	125	825	120	725	105	21	20	15
Udimet 630	Bar	1520	220	1380	200	965	140	1310	190	1170	170	860	125	15	15	5

Table 6 Effect of Temperature on the Mechanical Properties of Wrought Nickel-, Iron-, and Cobalt-Base Superalloys

Udimet 700	Bar	1410	204	1275	185	1035	150	965	140	895	130	825	120	17	16	20
Udimet 710	Bar	1185	172	1150	167	1020	148	910	132	850	123	815	118	7	10	25
Udimet 720	Bar	1570	228	_	_	1455	211	1195	173	_	_	1050	152	13	_	9
Unitemp AF2-1DA6	Bar	1560	226	1480	215	1290	187	1015	147	1040	151	995	144	20	19	16
Waspaloy	Bar	1275	185	1170	170	650	94	795	115	725	105	675	98	25	23	28
Iron Base																
A-286	Bar	1005	146	905	131	440	64	725	105	605	88	430	62	25	19	19
Alloy 901	Bar	1205	175	1030	149	725	105	895	130	780	113	635	92	14	14	19
Discaloy	Bar	1000	145	865	125	485	70	730	106	650	94	430	62	19	16	_
Haynes 556	Sheet	815	118	645	93	470	69	410	60	240	35	220	32	48	54	49
Incoloy 800	Bar	595	86	510	74	235	34	250	36	180	26	150	22	44	38	83
Incoloy 801	Bar	785	114	660	96	325	47	385	56	310	45	290	42	30	28	55
Incoloy 802	Bar	690	100	600	87	400	58	290	42	195	28	200	29	44	39	15
Incoloy 807	Bar	655	95	470	68	350	51	380	55	255	37	225	32.5	48	40	34
Incoloy 825 ^b	_	690	100	~590	~86	~275	~40	310	45	~234	~34	180	~26	45	~44	~86
Incoloy 903	Bar	1310	190	_	_	_	_	1105	160	_	_	_	_	14	_	_
Incoloy 907 ^c	_	~1365	~198	~ 1205	~175	~655	~95	~1110	~161	~960	~139	~565	~ 82	~12	~11	~ 20
Incoloy 909	Bar	1310	190	1160	168	615	89	1020	148	945	137	540	78	16	14	34
N-155	Bar	815	118	650	94	428	62	400	58	340	49	250	36	40	33	32
V-57	Bar	1170	170	1000	145	620	90	830	120	760	110	485	70	26	19	34
19-9 DL	_	815	118	615	89	_	_	570	83	395	57	_	_	43	30	_
16-25-6	_	980	142	_	_	415	60	770	112	_	_	345	50	23	—	11
Cobalt Base																
AirResist 213	_	1120	162	_	_	485	70	625	91	_	_	385	56	14	_	47
Elgiloy	_	690 ^b	100 ^b	_	_	_	_	480^{b}	70-290	_	_	_	_	34	_	_
		2480^{d}	360 ^d					2000^{d}								
Haynes 188	Sheet	960	139	740	107	635	92	485	70	305	44	290	42	56	70	43
L-605	Sheet	1005	146	800	116	455	66	460	67	250	36	260	38	64	59	12
MAR-M 918	Sheet	895	130	_	_	_	_	895	130	_	_	_	_	48	—	_
MP35N	Bar	2025	294	_	_	_	_	1620	235	_	_	_	_	10	—	_
MP159	Bar	1895	275	1565	227	_	_	1825	265	1495	217	_	_	8	8	_
Stellite 6B	Sheet	1010	146	_	_	_	_	635	92	_	_	_	_	11	_	_
Haynes 150	_	925	134	—	—	—	—	317	46	—	—	—	—	8	_	—

^aCold-rolled and solution-annealed sheet, 1.2–1.6 mm (0.048–0.063 in.) thick.

^bAnnealed.

^cPrecipitation hardened.

^{*d*}Work strengthened and aged.

Source: Metals Handbook Desk Edition, ASM International, Materials Park, OH 44073-0002, 1999, p. 409.

Table 7 Effect of Temperature on the Mechanical Properties of Cast Nickel-Base and Cobalt-Base Alloys

		Ultimate Tensile Strength at:						0.2% Yield Strength at:							
	21	21°C (70°F)		538°C (1000°F)		3°C 0°F)	21 (70	°C I°F)	538 (100	°C J°F)	109	3°C 0°F)	Tensile Elongation, % at:		
Alloy	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	21°C (70°F)	538°C (1000°F)	1093°C (2000°F)
Nickel Base															
IN-713 C	850	123	860	125	_	_	740	107	705	102	_		8	10	_
IN-713 LC	895	130	895	130		_	750	109	760	110	_		15	11	
B-1900	970	141	1005	146	270	38	825	120	870	126	195	28	8	7	11
IN-625	710	103	510	74		_	350	51	235	34	_	_	48	50	
IN-718	1090	158	_			_	915	133			_		11		
IN-100	1018	147	1090	150	(380)	(55)	850	123	885	128	(240)	(35)	9	9	
IN-162	1005	146	1020	148			815	118	795	115	<u> </u>	<u> </u>	7	6.5	
IN-731	835	121		_	275	40	725	105	_		170	25	6.5		
IN-738	1095	159		_			950	138	_		_		_		
IN-792	1170	170		_			1060	154	_		_		4		
M-22	730	106	780	113			685	99	730	106	_		5.5	4.5	
MAR-M 200	930	135	945	137	325	47	840	122	880	123	_		7	5	
MAR-M 246	965	140	1000	145	345	50	860	125	860	125	_		5	5	
MAR-M 247	965	140	1035	150			815	118	825	120			7		
MAR-M 421	1085	157	995	147			930	135	815	118	_		4.5	3	
MAR-M 432	1240	180	1105	160			1070	155	910	132	_		6		
MC-102	675	98	655	95			605	88	540	78	_	_	5	9	_
Nimocast 75	500	72	_	_			179	26	_	_	_	_	39		_
Nimocast 80	730	106	_	_			520	75	_	_	_	_	15		_
Nimocast 90	700	102	595	86			520	75	420	61	_	_	14	15	_
Nimocast 242	460	67	_	_			300	44	_	_	_	_	8		_
Nimocast 263	730	106		_	_	_	510	74	_	_	_		18		
René 77	_	_		_		_	_	_		_	_		_	_	_
René 80	_	_		_		_	_	_		_	_		_	_	_
Udimet 500	930	135	895	130		_	815	118	725	105	_		13	13	_
Udimet 710	1075	156		_	240	35	895	130	_	_	170	25	8	_	_
CMSX-2 ^a	1185	172	1295 ^b	188^{b}	_	_	1135	165	1245 ^b	181^{b}	_	_	10	17 ^b	_
GMR-235	710	103		_	_	_	640	93	_	_	_	_	3	_	18
IN-939	1050	152	915 ^b	133 ^b	325 ^c	47^{c}	80	116	635 ^b	92 ^b	205°	30 ^c	5	7^b	25
$MM \ 002^{d}$	1035	150	1035^{b}	150^{b}	550 ^c	85 ^c	825	120	860^{b}	125^{b}	345 ^c	50 ^c	7	5^{b}	12

IN-713 Hf ^e	1000	145	895 ^b	130 ^b	380^{c}	55 ^c	760	110	620 ^b	90^{b}	240°	35 ^c	11	6^b	20°
René 125 Hf ^f	1070	155	1070^{b}	155 ^b	550°	80°	825	120	860^{b}	125^{b}	345 ^c	50°	5	5^{b}	12^{c}
MAR-M 246 Hfg	1105	160	1070^{b}	155 ^b	565 ^c	82^{c}	860	125	860^{b}	125^{b}	345 ^c	50°	6	7^b	14^{c}
MAR-M 200 Hf ^h	1035	150	1035^{b}	150 ^b	540°	78^{c}	825	120	860^{b}	125^{b}	345 ^c	50°	5	5^{b}	10^{c}
PWA-1480 ^a	_		1130 ^b	164^{b}	685 ^c	99 ^c	895	130	905 ^b	131 ^b	495^{c}	72^{c}	4	8^b	20°
SEL	1020	148	875 ^b	127^{b}	_		905	131	795 ^b	115^{b}	_	_	6	7^b	_
UDM 56	945	137	945 ^b	137 ^b	_		850	123	725 ^b	105^{b}	_	_	3	5^b	_
SEL-15	1060	154	1090 ^b	158^{b}		_	895	130	815^{b}	118^{b}	—	—	9	5^b	—
Cobalt Base															
AiResist 13 ⁱ	600	87	420 ^b	61 ^b	_		530	77	330 ^b	48^{b}	_	_	1.5	4.5^{b}	_
AiResist 215 ⁱ	690	100	570 ^j	83 ^j	_	_	485	70	315^{j}	46^{j}	_	_	4	12^{j}	_
FSX-414	_	_	_	_	_	_	_	_		_	_	_		_	_
Haynes 1002	770	112	560	81	115	17	470	68	345	50	95	14	6	8	28
MAR-M 302	930	135	795	115	150	22	690	100	505	73	150	22	2	_	21
MAR-M 322 ⁱ	830	120	595 ^b	86 ^b	_		630	91	345 ^b	50^{b}	_	_	4	6.5^{b}	_
MAR-M 509	785	114	570	83	_		570	83	400	58	_	_	4	6	_
WI-52	750	109	745	108	160	23	585	85	440	64	105	15	5	7	35
X-40	745	108	550	80	_	_	525	76	275	40		_	9	17	_

^aSingle crystal [001].

^bAt 760°C (1400°F).

^cAt 980°C (1800°F).

^dRR-7080.

^eMM 004.

^fMM 005.

^gMM 006.

^hMM 009.

ⁱData from Vol. 3, 9th ed., Metals Handbook, 1980.

^{*j*}At 650°C (1200°F).

Source: Metals Handbook Desk Edition, ASM International, Materials Park, OH 44073-0002, 1999, p. 409.

Table 8 1000-h Rupture Strengths of Wrought Nickel-, Cobalt, and Iron-Base Superalloys

		Rupture Strength at:									
		650°C (1200°F)	760°C (1400°F)	870°C (1600°F)	980°C (1800°F)			
Alloy	Form	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi		
Nickel Base											
Astroloy	Bar	770	112	425	62	170	25	55	8		
Cabot 214	_	_	_	_	_	30	4	15	2		
D-979	Bar	515	75	250	36	70	10	_	_		
Hastelloy S	Bar	_	_	90	13	25	4	_	_		
Hastelloy X	Sheet	215	31	105	15	40	6	15	2		
Haynes 230	_	_	_	125	18	55	8	15	2		
Inconel 587	Bar	_		285	41			_			
Inconel 597	Bar	_		340	49			_			
Inconel 600	Bar	_			_	30	4	15	2		
Inconel 601	Sheet	195	28	60	9	30	4	15	2		
Inconel 617	Bar	360	52	165	24	60	9	30	4		
Inconel 617	Sheet	_		160	23	60	9	30	4		
Inconel 625	Bar	370	54	160	23	50	7	20	3		
Inconel 706	Bar	580	84	_			_				
Inconel 718	Bar	595	86	195	28		_				
Inconel 718 Direct Age	Bar	405	59	_			_				
Inconel 718 Super	Bar	600	87	_	_		_	_			
Inconel X750	Bar	470	68	_	_	50	7	_			
M-252	Bar	565	82	270	39	95	14	_			
Nimonic 75	Bar	170	25	50	7	5	1	_			
Nimonic 80A	Bar	420	61	160	23		_	_			
Nimonic 90	Bar	455	66	205	30	60	9	_			
Nimonic 105	Bar			330	48	130	19	30	4		
Nimonic 115	Bar			420	61	185	27	70	10		
Nimonic 942	Bar	520	75	270	39						
Nimonic PE 11	Bar	335	49	145	21		_	_			
Nimonic PE 16	Bar	345	50	150	22		_	_			
Nimonic PK 33	Sheet	655	95	310	45	90	13	_	_		
Pyromet 860	Bar	545	79	250	36			_	_		
René 41	Bar	705	102	345	50	115	17	_	_		
René 95	Bar	860	125	_	_	_	_	_	_		

Udimet 400	Bar	600	87	305	44	110	16		_
Udimet 500	Bar	760	110	325	47	125	18	_	_
Udimet 520	Bar	585	85	345	50	150	22	_	
Udimet 700	Bar	705	102	425	62	200	29	55	8
Udimet 710	Bar	870	126	460	67	200	29	70	10
Udimet 720	Bar	670	97	_	_	_	_	_	
Unitemp AF2-1DA6	Bar	885	128	360	52	_	_	_	
Waspaloy	Bar	615	89	290	42	110	16		
Iron Base									
A-286	Bar	315	46	105	15	_	_	_	
Alloy 901	Sheet	525	76	205	30	_	_	_	
Discaloy	Bar	275	40	60	9	_	_	_	
Haynes 556	Sheet	275	40	125	18	55	8	20	3
Incoloy 800	Bar	165	24	66	9.5	30	4.4	13	1.9
Incoloy 801	Bar	_		_	_	_	_		
Incoloy 802	Bar	170	25	110	16	69	10	24	3.5
Incoloy 807	Bar	_		105	15	43	6.2	19	2.7
Incoloy 903	Bar	510	74	_		_	—		
Incoloy 909	Bar	345	50	_		_	—		
N-155	Bar	295	43	140	20	70	10	20	3
V-57	Bar	485	70	_	—	—	—	_	_
Cobalt Base									
Haynes 188	Sheet	_	_	165	24	70	10	30	4
L-605	Sheet	270	39	165	24	75	11	30	4
MAR-M 918	Sheet	_	_	60	9	20	3	5	1
Haynes 150	_			40^{a}	5.8	—			_

^aAt 815°C (1500°F).

Source: Metals Handbook Desk Edition, ASM International, Materials Park, OH 44073-0002, 1999, p. 410.

Table 9 Stress-Rupture Strengths for Selected Cast Nickel-Base Superalloys

	Rupture Stress at:										
	815°C	(1500°F)	870°C	(1600°F)	980°C	(1800°F)					
Alloy	100 h MPa (ksi)	1000 h MPa (ksi)	100 h MPa (ksi)	1000 h MPa (ksi)	100 h MPa (ksi)	1000 h MPa (ksi)					
Nickel Base											
IN-713 LC	425 (62)	325 (47)	295 (43)	240 (35)	140 (20)	105 (15)					
IN-713C	370 (54)	305 (44)	305 (44)	215 (31)	130 (19)	70 (10)					
IN-738 C	470 (68)	345 (50)	330 (48)	235 (34)	130 (19)	90 (13)					
IN-738 LC	430 (62)	315 (46)	295 (43)	215 (31)	140 (20)	90 (13)					
IN-100	455 (66)	365 (53)	360 (52)	260 (38)	160 (23)	90 (13)					
MAR-M 247 (MM 0011)	585 (85)	415 (60)	455 (66)	200 (30)	185 (27)	125 (18)					
MAR-M 247 (NW 0011) MAR-M 246	525 (76)	435 (62)	440 (63)	290 (42)	105 (27)	125 (18)					
MAR-M 246 Hf (MM 006)	525 (70)	435 (62)	425 (62)	285 (41)	205 (20)	120 (10)					
MAR M 200	405 (77)	415 (60)	385 (56)	205 (43)	170 (25)	125 (18)					
MAR-M 200 Hf (MM 000)	495 (72)	413 (00)	585 (50)	295 (45)	170 (23)	125 (18)					
P 1000	510 (74)	280 (55)	295 (56)	250 (26)	180 (26)	125 (16)					
B-1900	510 (74)	580 (55)	363 (30)	230 (30)	180 (20)	(10)					
Rene //	_	_	310 (45)	215 (31.5)	130 (19)	62 (9.0)					
Rene 80			350 (51)	240 (35)	160 (23)	105 (15)					
IN-625	130 (19)	110 (16)	97 (14)	76 (11)	34 (5)	28 (4)					
IN-162	505 (73)	370 (54)	340 (49)	255 (37)	165 (24)	110 (16)					
IN-731	505 (73)	365 (53)			165 (24)	105 (15)					
IN-792	515 (75)	380 (55)	365 (53)	260 (38)	165 (24)	105 (15)					
M-22	515 (75)	385 (56)	395 (57)	285 (41)	200 (29)	130 (19)					
MAR-M 421	450 (65)	305 (44)	310 (46)	215 (31)	125 (18)	83 (12)					
MAR-M 432	435 (63)	330 (48)	295 (40)	215 (31)	140 (20)	97 (14)					
MC-102	195 (28)	145 (21)	145 (21)	105 (15)	_	_					
Nimocast 90	160 (23)	110 (17)	125 (18)	83 (12)	_	_					
Nimocast 242	110 (16)	83 (12)	90 (13)	59 (8.6)	45 (6.5)	_					
Udimet 500	330 (48)	240 (35)	230 (33)	165 (24)	90 (13)	_					
Udimet 710	420 (61)	325 (47)	305 (44)	215 (31)	150 (22)	76 (11)					
CMSX-2		_		345 (50)		170 (25)					
GMR-235	_	_	_	180 (26)	_	75 (11)					
IN-939	_	_	_	195 (28)	_	60 (9)					
MM 002	_	_	_	305 (44)	_	125 (18)					
IN-713 Hf (MM 004)	_	_	_	205 (30)	_	90 (13)					
René 125 Hf (MM 005)	_	_	_	305 (44)	_	115 (17)					
SEL-15	_	_	_	295 (43)	_	75 (11)					
UDM 56				270 (39)		125 (18)					
CDM 50				210 (37)		125 (10)					
Cobalt Base	150 (22)	05 (1.0)	115 (17)	00 (10)		50 (T)					
HS-21	150 (22)	95 (14)	115 (17)	90 (13)	60 (9)	50 (7)					
X-40 (HS-31)	180 (26)	140 (20)	130 (19)	105 (15)	75 (11)	55 (8)					
MAR-M 509	270 (39)	225 (33)	200 (29)	140 (20)	115 (17)	90 (13)					
FSX-414	150 (22)	115 (17)	110 (16)	85 (12)	55 (8)	35 (5)					
WI-52	—	195 (28)	175 (25)	150 (22)	90 (13)	70 (10)					

Source: Metals Handbook Desk Edition, ASM International, Materials Park, OH 44073-0002, 1999, p. 412.

310

mechanical properties. Concurrently, the availability of oxygen at high temperatures accelerates the conversion of some of the metal atoms to oxides. Oxidation proceeds much more rapidly at high temperatures than at room or lower temperatures.

2.2 Mechanical Behavior

In the case of short-time tensile properties (yield strength, ultimate strength), the mechanical behavior of metals at higher temperatures is similar to that at room temperature, but with metals becoming weaker as the temperature increases. However, when steady loads below the normal yield or ultimate strength determined in short-time tests are applied for prolonged times at higher temperatures, the situation is different. Figure 1 illustrates the way in which most materials respond to steady extended-time loads at high temperatures.

Owing to the higher temperature, a time-dependent extension (creep) is noticed under load. If the alloy is exposed for a long time, the alloy eventually fractures (ruptures). The degradation process is called creep or, in the event of failure, creep-rupture (sometimes stress-rupture), and alloys are selected on their ability to resist creep and creep-rupture failure. Data for superalloys frequently are provided as the stress that can be sustained for a fixed time (e.g., 100-h rupture) versus the temperature. Figure 2 shows such a plot with ranges of expected performance for various superalloy families. One of the contributory aspects of elevated temperature failure is that metals tend to come apart at the grain boundaries when tested for long times above about 0.5 of their absolute melting temperature. Thus, fine-grained alloys, which are usually favored for lower temperature applications, may not be the best materials for creep-rupture limited applications at high temperatures. Elimination or reorientation of grain boundaries is sometimes a key factor in maximizing the higher temperature life of an alloy.



Fig. 1 Creep-rupture schematic showing time-dependent deformation under constant load at constant high temperatures followed by final rupture. (All loads below the short-time yield strength. Roman numerals denote ranges of the creep-rupture curve.)



Fig. 2 Creep-rupture curves showing ranges for superalloy families. (From *Superalloys Source Book*, ASM International, Materials Park, OH 44073-0002, 1984, p. 3.)

Cyclically applied loads that cause failure (fatigue) at lower temperatures also cause failures in shorter times (lesser cycles) at high temperatures. For example, Fig. 3 shows schematically how the cyclic resistance is degraded at high temperatures when the locus of failure is plotted as stress versus applied cycles (S-N) of load. From the S-N curves shown, it should be clear that there is not necessarily an endurance limit for metals and alloys at high temperatures. Cyclic loads can be induced not only by mechanical loads in a structure, but also by thermal changes. The combination of thermally induced and mechanically induced loads leads to failure in thermal-mechanical fatigue (TMF). TMF failures occur in a relatively low number of cycles. Thus TMF is a low cycle fatigue (LCF) process while lower load mechanical fatigue leads to failure in a high number of cycles (HCF). LCF failures in structures can be mechanically induced or TMF-type. In airfoils in the hot section of gas turbines, TMF is a major concern. In highly mechanically loaded parts, such as gas turbine disks, LCF is the major concern. HCF normally is not a problem with superalloys unless a design error occurs and subjects a component to a high-frequency vibration that forces rapid accumulation of fatigue cycles.

While life under cyclic load (S–N behavior) is a common criterion for design, resistance to crack propagation is an increasingly desired property. Thus, the crack growth rate versus a fracture toughness parameter is required. The parameter in this instance is the stress intensity factor (K) range over an incremental distance which a crack has grown—the difference between the maximum and minimum K in the region of crack length measured. A plot of the resultant type (da/dn vs. ΔK) is shown in Fig. 4 for several wrought superalloys.

The nature of superalloys is that they resist the creep-rupture process better than other materials, have very good higher temperature short-time strength



Fig. 3 Stress versus cycles to failure (S–N) curves showing: (a) schematic typical fatigue response at high temperature vs. that at lower temperature and (b) actual fatigue curves at room and elevated temperature for a specific nickel-base superalloy.

(yield, ultimate), very good fatigue properties (including fatigue crack propagation resistance) and combine these mechanical properties with good to exceptional oxidation resistance. Consequently, superalloys are the obvious choice when structures are to operate at higher temperatures. Generally, the temperature range of superalloy operation is broken up into the intermediate range of about 540° C (1000°F) to 760°C (1400°F) and the high-temperature range that occurs above about 816°C (1500°F).



Fig. 4 Crack growth rate (da/dn) versus toughness change (ΔK) curves for several superalloys at 649°C (1200°F). Note that HIP = hot isostatically pressed and H + F = HIP + forge. Unless otherwise noted, all alloys are forged. (From *Superalloys II*, Wiley, 1987, p. 284. Used by permission.)

3 PROPERTIES OF SUPERALLOYS

3.1 Physical/Environmental

Iron, cobalt, and nickel, the bases of superalloys, are transition metals located in a similar area of the periodic table of the elements. The density, melting point, and physical properties of the superalloy base elements are given in Table 10. As can be seen, pure iron has a density of 7.87 g/cm^3 (0.284 lb/in.^3), while pure nickel and cobalt have densities of about 8.9 g/cm³ (0.322 lb/in.^3). The superalloys are created usually by adding significant levels of the alloy elements chromium, aluminum, and titanium, plus appropriate refractory metal elements such as tungsten and molydenum to the base metal. Densities of superalloys are a function of the amounts of these elements in the final compositions. For example, iron-nickel-base superalloys have densities of around $7.9-8.3 \text{ g/cm}^3$ ($0.285-0.300 \text{ lb/in.}^3$), not too dissimilar to densities of nickel-base superalloys, which may range from about 7.8 to 8.9 g/cm³ ($0.282 \text{ to } 0.322 \text{ lb/in.}^3$). Cobaltbase superalloy densities, on the other hand, range from about 8.3 to 9.4 g/cm³ ($0.300 \text{ to } 0.340 \text{ lb/in.}^3$). Aluminum, titanium, and chromium reduce superalloy

		Melting Point		Density		Expansion	Coefficient ^a	Thermal Conductivity ^a		
	Crystal Structure	°F	°C	lb/in ³	g/cm ³	$^{\circ}\mathrm{F} imes10^{-6}$	$^{\circ}\mathrm{C} imes 10^{-6}$	Btu/ft²/hr/°F/in.	cal/cm ² /s/°C/cm	
Co	НСР	2723	1493	0.32	8.9	7.0	12.4	464	0.215	
Ni	FCC	2647	1452	0.32	8.9	7.4	13.3	610	0.165	
Fe	BCC	2798	1535	0.28	7.87	6.7	11.7	493	0.175	

 Table 10
 Some Physical Properties of Superalloy Base Elements

^{*a*}At room temperature.

Source: From Superalloys II, Wiley, 1987, p. 14.

density whereas the refractory elements such as tungsten, rhenium, and tantalum increase it. Table 5 gives density, melting range, and physical properties of some nickel- and cobalt-base superalloys.

The melting temperatures of the basis superalloy elements are nickel at 1452°C (2647°F), cobalt at 1493°C (2723°F), and iron at 1535°C (2798°F). When metals are alloyed, there is no longer a single melting point for a composition. Instead, alloys melt over a range of temperature. The lowest melting temperature (incipient melting temperature) and melting ranges of superalloys are functions of composition and prior processing. Just as the basis metal is higher melting, so generally are incipient melting temperatures greater for cobalt-base superalloys than for nickel- or iron-nickel-base superalloys. Nickel-base superalloys may show incipient melting at temperatures as low as 1204°C (2200°F). However, advanced nickel-base single-crystal superalloys having limited amounts of melting-point depressants tend to have incipient melting temperatures equal to or in excess of those of cobalt-base superalloys.

The physical properties of electrical conductivity, thermal conductivity, and thermal expansion of superalloys tend to be low (relative to other metal systems). These properties are influenced by the nature of the base metals (transition elements) and the presence of refractory-metal additions.

The corrosion resistance of superalloys depends primarily on the alloying elements added and the environment experienced. Contaminants in the atmosphere can caused unexpectedly high corrosion rates. The superalloys employed at the highest temperatures are coated to increase oxidation/corrosion resistance. More information follows later in this chapter.

3.2 Mechanical

The superalloys are relatively ductile; the ductilities of cobalt-base superalloys generally are less than those of iron-nickel- and nickel-base superalloys. Short-time tensile ductilities as determined by elongation at failure generally range from as low as 10 pct to as high as around 70 pct, but γ' -hardened alloys are in the lower end, usually between about 10 and 40 pct. Creep-rupture ductilities generally are lower than tensile ductilities. At the 760°C (1400°F) tensile ductility minimum area, creep-rupture ductilities of castings have gone below 1.5 pct; however, most current high-strength PC equiaxed cast alloys have rupture ductilities in excess of 2.0 pct. Single crystal directionally solidified (SCDS) superalloy ductilities can vary with orientation of the single crystal relative to the testing direction.

Superalloys typically have dynamic moduli of elasticity in the vicinity of 207 GPa ($30^{\circ} \times 10^{6}$ psi), although moduli of specific polycrystalline (PC) equiaxed 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 about 124 to 310 GPa (about 18 to 45×10^{6} psi) depending on the relation of grain or crystal orientation to testing direction. Dynamic measurement of modulus of elasticity at high temperatures is necessary because static modulus is greatly influenced by high temperatures and shows significant reductions over the dynamic value at a common high temperature. Modulus may drop by around 25–30 pct as temperatures increase from room temperature to 871°C (1600°F).

Short-time tensile yield properties of γ' -hardened alloys range from around 550 MPa (80 ksi) to 1380 MPa (200 ksi) at room temperature. Actual values depend on composition and processing (cast vs. wrought). Wrought alloys tend to have the highest values, with the highest hardener content alloys (e.g., Rene 95, IN 100) having the highest strengths. However, strength is a function of grain size and stored energy and alloys such as U630 or IN 718 can be produced with very high yield strengths. Solid-solution-hardened alloys such as the sheet alloy, Hastelloy X, show lower strengths. Ultimate strengths range from around 690 MPa (100 ksi) to 1520 MPa (230 ksi) at room temperature, with γ' -hardened alloys in the high end of the range.

Superalloys tend to show an increase of yield strength from room temperature up to about 760°C (1400°F) and drop off thereafter. This is in contrast to ordinary alloys that tend to continuously decrease in short-time strength as temperatures increase. Ultimate strengths generally do not show this trend. Concurrently, tensile ductility tends to decrease, with a minimum at around 649°C (1200°F). Many published data for alloys do not show any or much of an increase in tensile yield strength over the range to 760°C (1400°F).

The highest tensile properties are found in the finer grain size wrought or powder metallurgy superalloys used in applications at the upper end of the intermediate temperature regime, perhaps to about 760°C (1400°F). The highest creep-rupture properties invariably are found in the coarser grain cast superalloys used in the high-temperature regime. Rupture strengths are a function of the time at which they are to be recorded. The 1000-h rupture stress capability is obviously lower than the 100-h capability. Creep capability also is a function of the amount of creep permitted in a test. For example, the time to 0.5, 1.0, 2.0, and 5.0 pct might each be valuable for design dependent on a component's intended use. It is much more difficult to find this information than it is to find creep-rupture capability information. Handbooks generally do not carry much creep information. Creep-rupture strengths for 100-h failure at 982°C (1800°F) may range from 45 MPa (6.5 ksi) for an older γ' -hardened wrought alloy such as U500 to 205 MPa (30 ksi) for the PC equiaxed cast superalloy Mar-M 246. Columnar grain and single-crystal alloys can be much stronger.

Cyclic properties are not commonly tabulated for superalloys. Properties of interest would be the 10^3-10^5 and 10^6-10^8 cycle fatigue strength capabilities. This could mean stress for a fixed-cyclic life-to-a-particular-sized crack or stress for a fixed-cyclic life-to-fracture for LCF regimes or only stress for a fixed-cyclic life-to-fracture for HCF regimes. Also, crack propagation rates versus toughness parameter (da/dN vs. ΔK) are desired. The life values, when available, lend themselves to tabulation, but the da/dN values are best represented by graphs. LCF strengths are usually related to an alloy's yield strength while HCF strengths are usually related to an alloy's used in the hottest sections of a gas turbine, there appears to be a relation of TMF strength to the creep strength of an alloy for a given alloy form, as for columnar grain directionally solidified (CGCS) nickel-base superalloys.

Superalloys usually are processed to optimize one property in preference to others. The same composition, if used in cast and wrought state, may have different heat treatments applied to the different product forms. Even when a superalloy is used in the same product form, process treatments may be used to optimize one property over others. For example, an alloy such as Waspaloy was made in wrought form for gas turbine disks. By adjustment of processing conditions, principally heat treatment, substantial yield strength improvements were achieved at the expense of creep-rupture strength.

4 EVOLUTION OF SUPERALLOYS

During the first quarter of the twentieth century, chromium was added at various times to cobalt, nickel, and iron. The resulting products were remarkably resistant to atmospheric (moisture-based) environments and to oxidation at high temperatures. By World War II, some of these alloys, including other alloy elements, had come into use for such applications as resistance wires, dental prostheses, cutlery, and furnace and steam turbine components. With the development of the gas turbine engine during the war, the need became apparent for corrosion-resistant materials to operate in demanding mechanical load conditions at high temperatures. At this point, the fledgling superalloy industry began to expand.

By modifying the stainless steels, higher strengths were achieved without the need for special high-temperature strengthening phases. Phases such as η (a nickel-titanium compound) or γ' (a nickel-aluminum compound) had been introduced into the nickel-chromium families of alloys just prior to the war to produce high strength at high temperatures. The increasing temperatures forced alloy developers to include these phases (η and γ') in the iron-base alloys to take the high-temperature strength characteristics beyond those of the modified stainless steels such as 19-9DL. Alloys were invented in Germany and, after modification, made their way to the United States as A-286 or V-57 and are still in use today.

Nevertheless, the need for creep-rupture strength continually increased. Some of this need was met in the early years by adapting a cobalt-base corrosion-resistant alloy (vitallium) for use in aircraft engine superchargers and, later, to airfoils in the hot sections of gas turbines. Similar cobalt-base superalloys are still in use today. However, creep-rupture requirements for aircraft gas turbine applications soon outstripped those of the iron-nickel-base superalloys and the cobalt-base superalloys, and so nickel-base superalloys, modified to provide more of the hardening phase γ' , became increasingly used.

4.1 Improvement of Superalloys by Chemistry Control

The production of superalloy components initially consists of some sort of melting process. The melting produces ingots that are either remelted, converted to billet, converted to powder for subsequent consolidation to a component, or investment cast. Remelting is used to produce an ingot that can be processed to billet for forging or to mill forms (e.g., bar stock). Until the start of the second half of the twentieth century, melting of superalloys was conducted in air or under slag environments. The properties of modern superalloys derive principally from the presence of many elements that are reactive with oxygen and so were being lost to some degree in the customary melting and casting processes of the time. When vacuum melting techniques were introduced to commercial production of articles, they were pioneered by superalloys. Vacuum melting enabled the production of superalloys containing higher amounts of the hardeners aluminum and titanium. Furthermore, the concurrent reduction in gases, oxides, and other impurities caused a significant improvement in the ductility of superalloys. With more hardener content, strengths of superalloys began to increase dramatically. Figure 5 shows the improvement in creep-rupture life achieved with the reduction in oxygen content.

5 MELTING AND CASTING PRACTICES

5.1 General Aspects

The development of superalloys as they are employed today is largely a story of the development of modern melting technology. Whether the final product is to be a forging or an investment casting, the essence of a superalloy's ability to create the properties desired hinges on the correct choice and adaptation of melting principles.

Superalloy melting practices may be classified as either primary (the initial melt of elemental materials and/or scrap that sets the composition) or secondary (remelt of a primary melt for the purpose of controlling the solidification structure). The melt type or combination of melt types selected depends upon both the alloy composition, mill form and size desired, properties desired, and sensitivity of the final component to localized inhomogeneity in the alloy.

5.2 Melting and Refining Superalloys

The two most common primary melt practices are argon-oxygen decarburizing treatment of electric arc processed metal (Arc-AOD) and vacuum induction melting (VIM). The two common secondary melt practices are vacuum arc re-



Fig. 5 Improvement of rupture life at 871°C (1600°F) and 172 Mpa (25 ksi) by reduced oxygen content produced by vacuum melting. (From *Superalloys Source Book,* ASM International, Materials Park, OH 44073-0002, 1984, p. 11.)

melting (VAR) and electro slag remelting (ESR). A few alloy mill products may be manufactured from cast ingots after only primary melting. For the majority of superalloys the common practice combinations are Arc-AOD + ESR, VIM + ESR, VIM + VAR, and VIM + ESR + VAR. Common material specifications, such as Aerospace Materials Specifications (AMS), will specify acceptable melting practices.

The Arc-AOD practice used for superalloys is little different from that used for stainless steels. An electric arc furnace is the recipient of the initial charge and uses power from an arc struck between graphite electrodes and the charge to heat and melt the charge. Once the charge melts, no further electric power is needed. Heat is input into the charge by injecting ("blowing") oxygen under the surface of the melt to react with elements such as aluminum, titanium, silicon, and carbon. A desulfurizing addition (usually CaO) is made. The slag formed by the oxidation products and the desulfurizing addition is physically removed from the furnace.

The deslagged charge is transferred to the AOD vessel, which is a refractorylined steel shell with "tuyeres" in the bottom. The tuyeres are used to inject a mixture of argon and oxygen into the molten bath. By controlling the ratio of argon to oxygen, the selective oxidation or reduction of elements may be accomplished. The principal element reduced is carbon. Elements that need to be retained in the melt (particularly chromium) may also be oxidized into the slag. However, additions of aluminum made to the heat will react with the slag and reduce the chromium back into the molten charge. There is no external source of heat to an AOD vessel. The molten charge is heated by making additions of aluminum and oxidizing them. Cooling is accomplished by adding solid scrap to the bath. When the desired composition and pouring temperature are reached, the heat is poured off into a teeming ladle and transferred to the electrode/ingot pouring system. Precautions are taken (shrouding of the pour stream with argon) to minimize the reaction of the pour stream with atmospheric gasses.

The other prevalent primary melt practice is VIM. The VIM furnace consists of a ceramic-lined crucible built up around water-cooled induction coils. The crucible is mounted in a vacuum chamber. The vacuum chamber may have several vacuum ports (of various sizes) built into it so that, without breaking vacuum:

- Charge material may be introduced into the crucible.
- Molds may be introduced into the chamber.
- Systems for removing slag from the pour stream (tundish) may be introduced.
- Sampling of the molten metal may be made for chemistry control.

The charge is separated into three types of components, virgin, reactive, and revert. Note that virgin material is usually elemental material but may also consist of any other type of material that has not been previously vacuum melted. Reactive elements refer to those elements that are strong oxide formers. These are usually the "hardener" elements (titanium, aluminum) in superalloys. Operation of the VIM consists of charging the virgin portion of the charge (minus the reactive portion) into the crucible. The furnace is pumped down (if not already under vacuum) and a measurement made of the increase in pressure (as a function of time) when the vacuum ports are blanked off. This "leak-up rate" is a measurement of the base furnace vacuum integrity. Power is applied to the induction coils. The magnetic fields produced induce a current in the charge material, heating the charge. When the charge is molten, it will evolve gas (refining). The rate of gas evolution is measured by taking leak-up rates. When consecutive stable leak-up rates are obtained, then refining (degassing) is complete. This produces the lowest possible oxygen in the alloy. Reactive additions are then made and revert is added. (Revert is previously vacuum-melted alloy that is of the same or nearly the same composition as the intended melt.)

Additions of some form of calcium are usually made to reduce sulfur in the charge by forming a CaS slag. A chemistry sample is taken and "trim" additions are made to bring the heat to a precise composition. The metal is (top) poured into the molds through a system for metal transfer which also minimizes slag entrainment and regulation of the pour rate. Cast product for direct processing (e.g., for investment casting) is referred to as ingot. Most often, the VIM product is intended for secondary melting and is referred to as an electrode, as both secondary processes consume this product in an electrically heated process.

Compared to VIM, Arc-AOD uses the lowest cost charge material and has higher production rates. That is, Arc-AOD is the lowest cost process. However, Arc-AOD is limited in its ability to precisely control composition in a narrow range (particularly for superalloys with high titanium levels) and also produces much higher oxygen content material. (Note that the choice of secondary melting process may compensate to some degree for the higher oxide inclusion content of the Arc-AOD process.)

Electro slag remelting is the most frequently used secondary melt process for Arc-AOD electrodes. In ESR, alternating current (AC) is applied to an electrode situated inside a water-cooled crucible containing a slag charge. The intended circuit of current is from the electrode, through the molten slag, through the solidifying ingot, through the water-cooled stool, and by symmetrically located buss bars back to the electrode. The slag is generally a CaF₂ base, modified by major additions of CaO, MgO, and Al₂O₃. Minor additions of TiO₂ and ZrO₂ may be made to counteract loss of titanium and zirconium during the melting process. (Note that minor compositional changes may occur during ESR.) The current passing through the slag keeps the slag molten. The molten slag melts the immersed face of the electrode. As the molten metal gathers into drops on the melt surface of the electrode, it is reduced in sulfur (through reaction with the CaF_2) and entrained oxides are incorporated into the slag. The fully formed drop falls through the slag and is collected in the water-cooled crucible. The slag, which has formed a solid layer against the cooled crucible wall, is partially remelted by the molten metal, but remains as a layer between the ingot and the crucible. As the electrode is consumed, an ingot is built up in the crucible. At any given time the ingot contains a pool of molten metal at the ingot top and a zone of liquid + solid between the solid portion of the ingot and the molten pool.

It should be noted that, for a given alloy, there is a critical thickness and angle (to the growth direction) of the liquid + solid zone at which the liquid in

that zone may form self-perpetuating channels in the solidification structure. Such channels are known as "freckles" and are of such high solute content that subsequent thermal treatment cannot eliminate the elemental concentration. Thus, the final product may contain channels of hard particles (from the high solute) which are very detrimental to fatigue properties. The more highly alloyed the material being melted, the smaller and shallower must be the liquid + solid zone in order to avoid freckle formation. The shape and thickness of the liquid + solid zone may be modified to be more resistant to freckle formation by reducing the melt rate (the rate of deposition of molten metal into the pool), reducing the ingot diameter or by improving the heat extraction from the sides of the crucible.

Vacuum arc remelting is used in preference to ESR where larger ingot sizes of highly alloyed materials are needed. VAR is a direct current (DC) process conducted in a vacuum. As occurs in ESR, the electrode is melted into a watercooled crucible. The melting is accomplished by initially striking an arc between the electrode face and the crucible stool. The arc melts the electrode face and the molten metal collects into drops that fall into the crucible to form an ingot against which the arc is maintained. Because there is no additional source of heat (as, e.g., the cap of molten slag in ESR) and no insulating slag skin on the ingot, the profile of the molten zone in VAR is generally shallower (than in ESR) for any given alloy, melt rate, and ingot diameter combination.

There is no compositional change in VAR with the exception of minor elements with high vapor pressures. Thus, residual amounts of detrimental elements such as bismuth and lead may be removed by VAR. Unfortunately, volatile elements such as magnesium (used for control of sulfide shape) are also removed. The removal of magnesium is generally compensated for by providing an elevated level in the primary melt process.

5.3 Pros and Cons of Remelted Ingot Processing

In VAR the interface between the ingot and the crucible does not contain the slag skin found in ESR. Instead, the surface of the ingot, being the first material to solidify, is low in solute elements. More importantly, any oxides or nitrides from the electrode are swept into this surface layer as they melt out of the electrode and onto the surface of the molten pool. This layer is called "shelf." A disruption in the arc stability may cause the arc to undercut a small section of this shelf. If this section drops into the pool, it is unlikely to remelt and thus forms an alloy lean "spot" that contains layers of entrapped oxide and nitride ("dirt"). These inhomogeneous regions are light or "white" etching and are known as "dirty white spots." Their generation is triggered by conditions that do not generally leave any electronic signature (at current levels of detection capability) in the VAR records. While robust VAR process parameters and good electrode quality may minimize the frequency of dirty white spot occurrence, their formation cannot be completely avoided. Thus, the possible presence of dirty white spots in a component (and the degree of their degradation of properties) must be considered in material/melt-process selection for a component.

In selecting ESR as the secondary melt practice, positive considerations are that ESR does not generally form dirty white spots, that ESR products may also have better hot workability than VAR products and that the process yield may be modestly higher (lower cost). Negative considerations are that ESR products cannot be made in large ingot sizes (compared to VAR) without the formation of freckles. The state of the art in ESR controls is such that, at sizes where ESR will normally not form freckles, some undetected abnormality in the melt may cause sufficient disruption that freckles will be produced anyway. ESR is not a robust process (with regard to avoiding defect formation) when operated toward the extreme end of its size capability. However, advances in ESR controls have allowed commercially useful ingots of ESR Waspaloy to be produced while maintaining an adequate distance from the melt regimes where freckle formation would become a concern. More highly alloyed materials (such as IN 718) cannot yet be robustly produced by ESR in similar sizes.

In selecting VAR as the secondary melt practice, positive considerations are that (for a given alloy) VAR will produce a larger ingot (than ESR) without the presence of freckles and that at the selected size the process should be much more robust (in freckle resistance) than is ESR. The principal negative consideration is that dirty white spots will exist in the ingot and that they cannot be detected and their removal assured.

Several producers of critical rotating components in the gas turbine industry have adopted the use of a hybrid secondary melt process: VIM to ensure a low oxygen, precise chemistry initial electrode is followed by ESR. The ESRed electrode will be clean and sound but may contain freckles. After VIM + ESR, the clean, sound electrode is then remelted by VAR. The improved cleanliness and soundness of the electrode facilitates VAR control. This product (referred to as "triple melt") has a much reduced frequency of dirty white spot occurrence compared to double melt (VIM + VAR) product. However, even in triple melt, dirty white spots will occur and must be considered in the component design. The trade-off is the additional cost of an extra processing step versus the enhanced resistance to premature component failure from dirty white spots.

6 COMPONENT PRODUCTION

6.1 Casting Practices to Produce Parts

The principal casting practice is to use investment casting (also known as the lost wax process). A reverse cast model of the desired component is made and wax is solidified in the resultant die. Then a series of these wax models are joined to a central wax pouring stem. The assembly is coated (invested) with appropriate ceramic, processed to remove wax, and fired to strengthen the invested ceramic mold. An alloy is remelted and cast into the mold. Upon solid-ification, a series of components in the desired form are attached to the central pouring stem. These objects, frequently turbine hot section airfoil components, are removed and then processed to desired dimensions.

Superalloy investment castings now are available in sizes from a few inches in length up to about 48 in. diameter. Turbine airfoils can now be made not only for aircraft gas turbines but also for land-based power turbines with airfoil lengths of several feet.

Conventional investment castings are polycrystalline (PC) equiaxed with more or less randomly oriented grains. Mechanical properties are nominally random but may show some directionality. Increased property strength levels have been achieved by columnar grain directional solidification (CGDS), which removes grain boundaries that are perpendicular to the applied principal load in turbine airfoils. Removal of these grain boundaries dramatically improved longitudinal (parallel to airfoil axis) creep-rupture properties of nickel-base cast superalloys. Transverse boundaries continue to be a problem but their effects are minimized by the addition of hafnium, which enhances grain boundary ductility. The ultimate solution is to directionally solidify a superalloy as a single crystal, i.e., a superalloy with no grain boundaries. Maximum creep-rupture strength in nickelbase superalloys now is achieved with single-crystal directionally solidified (SCDS) alloys.

An interesting benefit of directional solidification in nickel-base superalloys is the reduction of the elastic modulus in the primary solidification direction (parallel to the longitudinal axis). Reduced moduli mean less thermal stress on hot section airfoils and thus longer life in TMF.

Selection of cast superalloys is best conducted in conjunction with an investment casting foundry that can indicate the likelihood of success in casting a given design in the alloy selected. Not all alloys are equally good for casting. Casting defects occur and vary with the alloy composition and casting practice. Traditionally, porosity is a major concern, especially with large castings for the cases of gas turbines. Porosity may be controlled by mold design and pouring modifications. Non-surface-connected porosity may be closed by hot isostatic pressing (HIP) of cast articles. Surface porosity in large castings may be repaired by welding. Other casting concerns have included intergranular attack (IGA) caused during chemical removal of molding materials, selectively located coarse grains in PC materials, misorientation and spurious grains in DS alloys, etc. Alloys may be modified in chemistry to optimize product yield but with a possible compromise in properties. Product yield will be an important determinator of final component cost.

6.2 Forging and Powder Metal Superalloys

Forging is the most common method of producing wrought components for superalloy applications. Mill products such as bar stock, wire, etc. are produced, but the most demanding applications use forged wrought ingot metallurgy components. Disks are forged to near-net size or to approximate shape using large presses and appropriate billets from previously produced ingots. The forging process requires the application of heat and pressure to move the alloy from its billet or powder metallurgy preform stage to a finished disk. One or more intermediate shape stages usually are involved when conventional forging is practiced. Isothermal (usually superplastic) forging may go directly from billet to final stage in one step.

As alloy strengths increased, it became increasingly difficult to move the alloy around during forging. Higher pressures were required and defects became more probable. Superplastic forging (isothermal forging) became available in the time frame when the strengths of superalloys were bumping up against metallurgical limits. In addition, the discipline of powder metallurgy opened the way to create billets of the highest strength alloys without the positive segregation defects (of alloy elements) that were making casting and forging of billets to final parts so difficult. In powder metallurgy, used principally for alloys such as Rene 95, IN 100 or other advanced alloys, a preliminary ingot is remelted and then atomized to small droplets that solidify with limited or no segregation of alloy elements. The powders thus produced are subsequently compacted together by HIP or by extrusion and processed to achieve 100-pct density. The aggregates are homogenous and display uniform properties. Sometimes the powder is pressed to form the final size/shape directly, but usually the powder is compacted to an intermediate stage (e.g., extruded billet) and isothermally forged to final form. Powder metallurgy is expensive, but the savings in subsequent machining costs and the ability to control defects make a reasonable cost trade. Possible defects in PM include carbide stringers and ceramic inclusions from the powder production process.

Conventional alloys such as Waspaloy, U 720, and IN 718 are produced by ingot metallurgy and standard forging practices. High-strength alloys such as Rene 95, IN 100, and Rene 88 generally are produced using powder metallurgy techniques.

6.3 Joining

Components of superalloys often could be advantageously produced or repaired by joining processes in the fledgling days of the superalloy industry. That is not necessarily true today. Cobalt-base superalloys, which do not depend on precipitated phases for strength generally are amenable to fusion welding. Sheet metal structures have been fabricated and repair welding is routinely practiced on cobalt-base superalloys. Wrought solution-hardened iron-nickel-base superalloys can be welded, but most precipitation-hardened versions are done with difficulty. Precipitation-hardened alloys tend to crack on fusion welding and properties of many precipitation-hardened alloys are degraded by the heat of the joining processes. These same concepts apply to the precipitation-hardened nickel-base superalloys, which become increasingly more difficult to weld as the amount of hardener in an alloy increases. An exception is the nickel-base (sometimes called nickel-iron-base) superalloy IN 718 which uses large amounts of niobium to harden the alloy. Figure 6 shows the relationship between hardener content and weldability for nickel-base superalloys.

While inertia bonding (nonfusion process) has been used to join nickel-base superalloys, conventional fusion welding is not customarily used successfully although electron beam welding may be useful. Other solid-state joining processes such as transient liquid-phase (TLP) bonding have been used with some measure of success.

The essence of the joining situation for superalloys is that nickel-base airfoils are not repair welded if cracks appear. Cobalt-base airfoils, on the contrary, may be welded to extend life. Sheet metal of cobalt-base, solid-solution-strengthened nickel-base and of lower hardener content nickel-base alloys can be joined and repair welded, as can iron-nickel-base alloys. The nickel-base alloy of choice for components requiring welding is IN 718, which, owing to the unique aspects of its hardening by γ'' , can be fusion welded with relative ease.

6.4 Summary of Manufacturing Process

Figure 7 presents a view of the superalloy manufacturing process. Many producers have been involved in the business of producing superalloys over the



Fig. 6 Weldability diagram for some γ' -strengthened nickel-base superalloys showing the influence of total age hardening elements (Al plus Ti) on cracking tendency. (From *Superalloys II*, Wiley, 1987, p. 152. Used by permission.)

years. During the past 50 years of progress, many advances have been made. New companies have formed and others gone out of business. Following are some current sources of superalloy expertise in ingot melting, component forging, and article casting:

General Information

ASM International, Materials Park, OH; www.asminternational.org

- Nickel Development Institute, Toronto, ON, Canada; www.nidi.org
- Cobalt Development Institute, Guildford Surrey, UK; www.cobaltdevinstitute.
- International Chromium Development Institute, Paris, France; www. chromium-assoc.com

Specialty Steel Industry of North America, Washington, DC; www.ssina.com

The Minerals, Metals & Materials Society, American Institute of Mining, Metallurgical and Petroleum Engineers New York, NY; www.tms.org

Melting/Ingot Production, Forming and/or Mill Products

Special Metals Corporation with locations at New Hartford, NY, Huntington, WV, and Hereford, UK; www.specialmetals.com

Carpenter Technology Corporation, Wyomissing, PA; www.cartech.com Haynes International, Kokomo, IN; www.haynesintl.com



Fig. 7 View of the superalloy manufacturing process. (From Superalloys II, Wiley, 1987, p. 23. Used by permission.)

- Teledyne Allvac, An Allegheny Technologies Co., Monroe, NC; www. allvac.com
- Cannon-Muskegon Corp., Subsidiary of SPS Technologies, Muskegon, MI; www.greenvillemetals.com/cmgroup.htm
- Howmet with locations worldwide, including Dover, NJ, and Devon, UK; www.howmet.com
- Doncasters PLC with locations including Sheffield, UK; www.doncastersbramah.com

Precision Rolled Products, Florham Park, NJ; No web site

Investment Castings

- Howmet Corp. with locations including Hampton, VA, Whitehall, MI, LaPorte, IN, Wichita Falls, TX, and Devon, England, Gennevilliers, France, Dives, France, and Terai, Japan; www.howmet.com
- Precision Cast Parts with locations including Minerva, OH, Cleveland, OH, Mentor, OH, and Douglas, CA; www.precast.com
- Doncasters Precision Castings with locations including Droitwich, Worcs, UK; www.doncasters-deritend.com; Bochum, Germany; www.doncasters-bochum.com, and Groton, CT; www.doncasters.com
- Hitchiner Manufacturing Co., Inc. Gas Turbine Div., Milford, NH; www. hitchiner.com

Forgings

- Wyman Gordon Co. with locations including N. Grafton, MA, Livingston, Scotland, and Houston, TX; www.wyman-gordon.com
- Schlosser Forge, Cucamonga, CA; www.aerospace-engine-parts.com
- Ladish Co, Inc., Cudahy, WI; www.ladish.com
- Carlton Forge Works, Paramount, CA; website unknown
- Carmel Forge, Tirat Carmel, Israel; website unknown
- Doncasters PLC with locations including Monk Bridge, UK; www.doncastersmonkbridge.com, Blaenavon, UK; www.doncasters-blaenavon.com, and Leeds, UK; www.doncasters.com
- Thyssen Umformtechnik, Remscheid, Germany; www.tut-gmbh.com Fortech, Clermont–Ferrand, France; website unknown
- Firth Rixson with locations including Monroe, NY, and Verdi, NV; website unknown
- Forged Metals, Fontana, CA; website unknown

Coating and/or Refurbishment/Repair

Chromalloy Gas Turbine Corp. with locations including Carson City, NV, Gardena, CA, Orangeburg, NY, Harrisburg, PA, Middletown, NY, Columbus, IN, Manchester, CT, and Phoenix, AZ; websites including www.chromalloy-cnv.com, www.chromalloy-cla.com, and www. chromalloyhit.com

7 OTHER ASPECTS OF SUPERALLOY SELECTION

Sermatech International Inc. with locations including Limerick, PA, Muncie, IN, Houston, TX, and Manchester, CT; www.sermatech.com

This list almost certainly will change and only should be used as a guide to locate potential producers. Most consumers deal with the forging and investment casting vendors who produce the product for subsequent final processing. For best control of properties, many consumers maintain liaison with melters and frequently audit all aspects of the manufacturing process. It is vital to remember in superalloy selection that most superalloys are not off-the-shelf consumer items. They are made to user specifications that may vary from user to user and time to time. Diligence in working with the producers will pay dividends in optimum properties and fewer difficulties for users of superalloys. This concept is indigenous to the industry and superalloy users for mission-critical or humanlife-critical applications. It is more costly than buying off-the-shelf. For some applications such as in oil development or coal gasification, there may be less stringent controls that permit off-the-shelf purchase of mill products. No forging or investment casting is an off-the-shelf item.

7 OTHER ASPECTS OF SUPERALLOY SELECTION

7.1 Corrosion and Coatings for Protection

Initial superalloys were intended to achieve strength with adequate oxidation resistance, and this was accomplished with superalloys that contained upward of 20 pct chromium. Oxidation resistance up to temperatures around 982°C (1800°F) was excellent. However, to increase the design flexibility of nickel-base superalloys, chromium content was reduced to permit more hardener to be added. Concurrently, some superalloys were put into service with environments (e.g., marine salts) that intensified oxidation or ion-induced attack such as hot corrosion. Also, the operating temperatures (surface environment temperatures) to which the alloys are exposed in the most demanding high-temperature conditions increased with the strength increases of the available alloys.

At higher temperatures, the chromium oxide formed during prior heat treatment was less protective and did not regenerate with exposure to high temperatures. General oxidation and intergranular oxidation along the grain boundaries of superalloys began to be a problem with chromium-protected superalloys, However, the problem was not as great as anticipated owing to the protective nature of aluminum oxide formed in greater amounts by the higher aluminum values of second- and third-generation γ' -hardened superalloys. Nevertheless, general oxidation occurred and still reduced cross sections, thus effectively increasing stresses in the remaining material. The grain boundary oxidation created notches. The combination of these events was of concern, and to protect against them, coatings were applied to superalloys.

The early coatings were diffusion coatings produced by pack aluminizing or slurry application. Chemistry of the coating was determined by the chemistry of the alloy. Later coatings were produced by overlaying a specific chemistry of a protective nature on the surface of the component using an appropriate physical vapor deposition unit. The diffusion-type coatings can coat internal (non-lineof-sight) surfaces, while the overlay coatings can only coat external surfaces that can be seen by the coating apparatus. The diffusion coatings are cheaper and, for a given thickness, probably nearly as protective as the overlay coatings. However, the overlay coatings can be made nearly twice as thick as the diffusion coatings, so overlay coatings often are the coatings of choice for turbine airfoil applications. Diffusion coatings are used to coat internal cooling passages in hot-section airfoils. Some commercial diffusion coating processes are available but virtually all overlay coating processes have been developed by superalloy users such as the aircraft gas turbine manufacturers.

Overlay coatings are generally more expensive than diffusion coatings. Some diffusion coatings are deposited in conjunction with precious metals such as gold or platinum. There are significant benefits to this incorporation of the noble metals in the coating but costs do go up.

Coating and corrosion technology are complex and do not lend themselves to a simple overall description and formula for protection. Hot corrosion phenomena are found below about 927°C (1700°F). Coatings and higher chromium content of an alloy act to inhibit surface attack. Coatings, in general, preserve the surface so that a component may be reused by removing and then restoring the coating.

Coating selection will be based on knowledge of oxidation/corrosion behavior in laboratory, pilot-plant, and field tests. Attributes that probably will be required for successful coating selection include:

- High resistance to oxidation and/or hot corrosion
- Ductility sufficient to provide adequate resistance to TMF
- Compatibility with the base alloys
- Low rate of interdiffusion with the base alloy
- Ease of application and low cost relative to improvement in component life
- Ability to be stripped and reapplied without significant reduction of basemetal dimensions or degradation of base-metal properties

7.2 Special Alloys for Hot-Corrosion Resistance

As temperature decreases below about 927°C (1700°F), the amount of hot corrosion attack decreases. At temperatures below around 760°C (1400°F), under certain conditions the hot corrosion mechanism changes. Attack may begin to increase dramatically with decreasing temperature but then decreases once more as temperatures drop below about 649°C (1200°F). In this lower temperature regime, the province of land-based power gas turbines, attack is resisted best by producing chromium oxide on the surface. Consequently, alloys for this region and application are those such as IN 738 specifically designed to have higher chromium levels, sometimes back up above 20 pct. (IN 939 is an alloy in this latter category.) Other alloys were devised for optimum hot corrosion resistance in higher temperature service. Rene 80 and IN 792 are such alloys.

7.3 Thermal Barrier Coatings

Allied with superalloy protective coating technology is the development of ceramic, so-called thermal barrier coatings (TBC). TBCs aim to reduce a superalloy's surface temperature by several hundred degrees, enabling a superalloy to operate at lower temperatures in a region where the superalloy may have higher strength. TBCs have found use and can be tailored to operate on a wide range of alloys. TBCs make use of overlay coating technology. A thin overlay coat serves as the bond interface between the ceramic of the TBC and the base superalloy.

8 ALLOY SELECTION SUMMARY

8.1 Intermediate-Temperature Applications

Available Alloys

Wrought alloys generally are used. Waspaloy and Astroloy were standard nickelbase superalloys selected in the past. Waspaloy is available but Astroloy may not be as readily procured. U-720 has found many applications.

Castings may be used for some applications of significant physical size. Large case structures for gas turbines are routinely cast in IN 718. However, in most instances, wrought alloys generally are used. Ductilities and fracture toughness of wrought alloys are better than those of cast alloys. Strength in tensile tests usually is better too. Creep may be of concern but rupture life normally is not an issue. Iron–nickel alloys such as A-286 might be considered as they may have sufficient strength and will be considerably less costly than their nickel-base counterparts. The best alloy to consider is the nickel-base (sometimes called nickel-iron-base) superalloy IN 718.

Superalloy IN 718 is the most widely used superalloy today. As a wrought alloy, it can be made in various strength levels and is the most weldable highstrength superalloy available. IN 718's weldability is a significant factor in its application as large cast cases.

Costs of IN 718 are lower than some other superalloys because of the widespread use of the alloy. IN 718 also is unique in that it contains none of the strategic element cobalt. IN 718 received a significant application boost in the late 1970s when a cobalt "shortage" caused the price of cobalt to soar to astronomical levels. IN 718 at that time faced continued competition from alloys such as Waspaloy and Astroloy. The lack of cobalt in the alloy swung the pendulum to IN 718 and in the succeeding 20 years, IN 718 has solidified its position as the most widely used superalloy.

In lieu of IN 718, alloys such as Waspaloy, U-720, and others can be adapted to designs. Powder metal techniques allow IN 100, Rene 95, and other high-strength and damage-tolerant alloys to be fabricated and used. An important trend in the intermediate temperature area is the development of dual material/property gas turbine disks. One of the major concerns for gas turbine disks is the difficulty of getting all desired properties in one material. Extensive work has been done to validate the position that a disk may be made of more than one material. Demonstrations have shown that creep-resistant rims can be attached to different core materials which emphasize brute-strength and fatigue resistance. Selection of such materials for an application, however, would require extensive alloy/process development.

What to Look for in Wrought Alloys

If alloys to be used are intended for massive applications such as turbine disks, high tensile yield and ultimate strength are desired. Good tensile ductility is important and good mechanical LCF behavior with acceptable crack propagation rates at expected load is a must. If an alloy is to be used as sheet, then good formability is a must, coupled with good weldability. Massive parts such as disks can benefit from good forgeability, but such a quality generally does not exist when high tensile strengths are required. Powder metallurgy processing enables production of forged components not otherwise processable. Inspectability of sonic finished shapes is crucial. Cost is a very important factor, but one that may have to be subverted to properties and processing if a desired component is to be made. Of course, use of special processing techniques such as powder metallurgy may enable a part to be formed that could not be made in any other way and so a high cost may be worth paying.

The essence of superalloy selection for intermediate temperature applications is that there are conventional alloys of capability similar to Waspaloy and down that can be procured and forged by conventional means. Similarly, sheet alloys are available that can be manipulated in conventional ways. For the higher strength applications, there are no easy off-the-shelf technologies or alloys that can just be picked from a catalog and put to work. Selection of alloys is a preliminary step that must be expanded upon to get data and components in a reasonable time frame at acceptable costs.

8.2 High-Temperature Applications

Available Alloys

The highest temperature applications invariably require cast superalloys where the requirement of maximum high-temperature strength is concerned. Some applications, such as combustion chambers, may require less strength and sheet alloys are applied. Nickel- and cobalt-base sheet is available. Hastelloy X, IN 617, HA 188, and others have long experience records. HA 230 has been used extensively. Property data generally are available for these alloys. The material purchased is a mill product and normally is readily available.

Turbine airfoil alloys or some combustor nozzles require stronger alloys than the old standby cobalt-base and early nickel-base PC cast alloys. Many of these highest strength alloys are proprietary to various companies, usually aircraft engine providers. The strongest alloys are the single-crystal nickel-base superalloys.

Cast superalloys for the bottom end of the high-temperature application spectrum may be those standbys such as IN 713 or even cobalt-base alloys such as X-40, which have decades of experience. IN 713 is a good general-purpose PC equiaxed casting alloy that also happens to have no cobalt. Alloys for higher temperatures include U-700, Rene 80, IN 792, IN 100 (Rene 100), Mar-M 246, Mar-M 247, Mar-M 200CG (PWA 1422), Rene 125, PWA 1480, Rene N4, and CMSX alloys such as CMSX-6. Some alloys (PWA 1422, Rene 125) are used only as CGDS components and others only as SCDS components (PWA 1480, Rene N4, most CMSX alloys). Alloys such as Rene 80 have been available in CGDS as well as PC equiaxed form. Others such as IN 792 have been available not only as PC equiaxed components but also in single-crystal form. A defining feature of the short list above is that nearly half of the alloys mentioned are associated with specific aircraft gas turbine companies. Although non-U.S. alloys were omitted from the list, some non-U.S. alloys also tend to be associated with specific manufacturing company ownership. Thus, many of the alloys that satisfy the most demanding environments may not be available for applications outside of their corporate patent realm.

What to Look for in Cast Alloys

If alloys are to be used for turbine airfoils, high creep and creep-rupture strengths are required. To maximize strength, the alloys for the most demanding applications in high-pressure turbine (HPT) sections should be SCDS materials. In addition to maximizing creep-rupture strength, TMF strength is optimized by the reduction in modulus achieved by orienting a specific direction of the superalloy crystal parallel to the airfoil axis. An alloy for the most stringent turbine airfoil applications will have a high melting point and good to excellent oxidation resistance, the ability to accept a coating and good LCF strength at temperatures where the airfoil attachment is made to a disk. These temperatures are around 760°C (1400°F). SCDS processing will also ensure that thin section properties are optimized. As section thickness is reduced, for a fixed load, a superalloy ruptures in less time than a standard thick test bar would fail. The order of property reduction is PC equiaxed, most reduced; CGDS, less; and SCDS, least.

For turbine vanes where no centrifugal load exists, airfoils may be made from PC equiaxed high-strength cast cobalt-base alloys instead of DS processed nickel-base alloys. High incipient melting temperature is desired for first-stage turbine vanes. A special type of superalloy, an oxide dispersion-strengthened (ODS) alloy has been used for turbine vanes in some applications. One such alloy, MA 754, relies on yttria dispersed in a corrosion-resistant nickel-chromium matrix to provide adequate creep-rupture capability. ODS alloys are not common. MA 6000 is another such alloy that may have enough strength for a high-pressure turbine blade in aircraft gas turbines. A problem with PC equiaxed airfoils is that the thermal mechanical stresses are much higher than on CGDS or SCDS parts owing to the higher modulus of PC equiaxed parts. The modulus of the CGDS and SCDS parts may be only 60 pct of the value for the PC equiaxed nickel-base cast alloys. In the most demanding conditions, TMF problems must be minimized by using oriented grain or crystal structures to reduce stresses.

For low-pressure turbine (LPT) airfoils, alloys such as the IN 100 (Rene 100) or IN 792 and Rene 80 PC equiaxed alloys previously used for HPT airfoils may be chosen. If temperatures or stress conditions are sufficiently relaxed, IN 713, U700, or similar first-generation PC equiaxed cast nickel-base superalloys may suffice.

9 FINAL COMMENTS

Many superalloys are available but not so many have been adopted for use. A principal reason for this situation is the high cost of proving the worth and safety of a new material. Within most aircraft engine companies, only a few airfoil alloys and a comparably short list of disk alloys have ever made it to production. Admittedly this list differs from company to company but the message is the same. If an existing alloy works and a new alloy does not offer some benefit

that overrides the development cost of proving up the alloy for its new use, do not change alloys.

If an alloy selector is starting from scratch to pick an alloy for an application, then any commercially available alloy may be fair game. On the other hand, the best alloy may not be available owing to corporate patent protection. Then, selection of another alloy from a superalloy producer may be necessary but may possibly require extensive development costs to get the product in workable form and to determine design properties. If possible, select a known alloy that has more than one supplier and more than one casting or forging source. Work with the suppliers and others in the manufacturing chain to acquire typical or design properties for the alloy in the form it will be used. Generic alloys owned by superalloy melters or developers are best for the alloy selector not associated with one of the big corporate users of superalloys. Companies with proprietary interests usually have nothing to benefit from giving up a technological advantage by sharing design data or even granting a production release to use a proprietary alloy.

BIBLIOGRAPHY

Betteridge, W., and J. Heslop, *The Nimonic Alloys*, 2nd ed., Crane, Russak and Co., New York, 1974. Davis, J. R. (ed.), *Heat-Resistant Materials* (an ASM Specialty Handbook) ASM International, Ma-

- terials Park, OH, 1997.
- Directory of Materials Property Databases, Advanced Materials and Processes, Special Supplement, ASM International, Materials Park, OH, Aug. 2000.
- Donachie, M. J. (ed.), *Superalloys Source Book*, American Society for Metals, Materials Park, OH, 1984.
- Donachie, M. J., and S. J. Donachie, *Superalloys: A Technical Guide*, 2nd ed., ASM International, Materials Park, OH, to be published.
- Lai, G. Y., *High Temperature Corrosion of Engineering Alloys*, ASM International, Materials Park, OH, 1990.
- The proceedings of a continuing series of conferences in Europe, first held in 1978 and at 4-year intervals thereafter, with emphasis on gas turbines, power engineering, and other applications (initial proceedings published as follows: *High Temperature Alloys for Gas Turbines*, Applied Science Publishers, 1978).
- The proceedings of a continuing series of conferences in the United States, first held at Seven Springs Mountain Resort, Champion, PA, in 1968 and at 4-year intervals thereafter with emphasis on high-temperature materials (initial proceedings published as follows: *International Symposium on Structural Stability in Superalloys*, Vol. I & Vol. II, AIME, New York, 1968).
- The proceedings of a continuing series of conferences in the United States, first held in 1989 and at irregular intervals thereafter, with emphasis on the metallurgy of IN 718 and related alloys (initial proceedings published as follows: *Superalloy 718 Metallurgy and Applications*, AIME, New York, 1989).
- The proceedings of a series of conferences in the United States published as follows: *Heat-Resistant Materials* and *Heat-Resistant Materials-II*, ASM International, Materials Park, OH, 1991 and 1995.
- Property data on CD-ROM, disk, or in a handbook form from ASM International (e.g., *Atlas of Creep and Stress Rupture Curves*, ASM International, Materials Park, OH, 1988).
- Property data handbooks published under the auspices of various government agencies.
- Sims, C. T., N. J. Stoloff, and W. C. Hager (eds.), Superalloys II, Wiley, New York, 1987.
- Sullivan, C. P., M. J. Donachie, and F. R. Morral, *Cobalt-Base Superalloys 1970*, Cobalt Information Center, Brussels, 1970.