

# **The Superalloys**

**Vital High Temperature Gas Turbine  
Materials for Aerospace and Industrial Power**

**EDITED BY**

**CHESTER T. SIMS**

**WILLIAM C. HAGEL**

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*General Electric Company*

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## FOREWORD

For the nearly three decades since the middle of World War II, the insatiable demands of the turbine engines that power our high performance military and commercial aircraft, as well as our industrial turbines, have motivated a search for new materials. These materials are for use at high temperatures in one of the most complex and difficult environments ever encountered. During this entire period, the materials technologist has met these demands with ever-improving superalloys, which, in addition to their increased use in engines as temperatures are pushed further upward, have become important to many other applications.

It has often been said that the opportunities in superalloys are exhausted; therefore, other materials of much higher melting point, such as chromium, the refractory metals, and ceramics, have been studied. Solutions to their problems have eluded our best efforts, however, and as yet none has found its way into engines. Instead, the pursuit of better and better superalloys continues with more ingenuity and imagination than that for any other alloy system. Indeed, the great need for improved superalloys has required exploration at the frontiers of metallurgical innovation, as aptly described in this volume. Although the already-demonstrated useful strength of the superalloys at the highest fraction of the base metal melting point of any alloy system has been achieved in part by the favorable properties that nature has bestowed on nickel and cobalt, the innovative efforts of the creative materials scientist and technologist are a tribute to ingenuity and the state of science.

An examination of *The Superalloys* reveals that even after years of endeavor, the current areas of pursuit are many and innovative, with yet further advances anticipated. The sophisticated approaches of powder metallurgy and thermomechanical processing, from the use of superplasticity to the achievement of ultrafine grain sizes and unique characteristics, suggest that a doubling of strength is possible for materials now in service for the intermediate temperatures from 800° to 1400°F (460° to 760°C). The use of powder metallurgy to achieve uniquely stable structures by mechanically dispersing unusual strengthening particles such as oxides is also coming to fruition. Yet, the exploration of new alloy compositions uniquely tailored to these sophisticated processing methods has only begun. Certainly the alloy compositions best suited for consolidation by conventional melting and forging or precision casting are not necessarily the same as those best suited for these new processes.

To meet the demands of increased strength, particularly for thermal fatigue resistance for turbine blades and vanes, the superalloy technologist has evolved methods of directional solidification or controlled grain growth

whereby all crystals are aligned along the length of the component, thus eliminating weakening transverse boundaries. He has even gone a giant step further to produce single crystal components with no grain boundaries at all!

To push temperature capability a step higher, he has suggested that he should be able to control solidification of eutectic alloys to grow aligned single crystals, or whiskers, from the eutectic phase within a ductile matrix to form a fiber-reinforced alloy of great strength and stability at very high temperatures. New directionally solidified eutectics of exceptional strength are now evolving. Of course, much remains to be done before these materials can be produced economically and before the necessary thermal fatigue and impact resistances are demonstrated.

Perhaps in superalloys more than in any other system, the metallurgist has been encouraged to use his cleverest ideas to demonstrate his ability to tailor alloys to a specific need. Materials technologists in other fields should benefit by these approaches.

A major barrier to the increase in use temperature of alloy systems for engines is oxidation and hot corrosion. Corrosion has become a more difficult problem to overcome than strength and ductility. Many current alloys are coated for use at high service temperatures. But the coatings are consumed eventually, both by their slow reaction with atmosphere at the surface and by diffusion with the substrate (usually to the detriment of the substrate properties). Thus, coatings wear out. Novel strengthening methods, such as particle dispersion and fiber metallurgy, for those compositions having the very best uncoated oxidation resistance are needed to obtain maximum possible life at maximum temperatures. Because of the inherent oxidation resistance of superalloy systems, this advance will most likely occur through use of a superalloy matrix.

The future of superalloys will be one of advanced understanding in physical metallurgy and corrosion, of advances in alloy consolidation and processing to control structure and thus properties, and of the creation of new metallurgical structures tailored to meet a need — a dramatic demonstration of the opportunity to meet the needs of the future through innovation in metallurgy. This volume covers the subject of superalloys in a timely, authoritative, and complete manner. The authors and editors are to be congratulated for an outstanding book.

G. Mervin Ault  
Director of Space Technology and Materials  
NASA Lewis Research Center

# Preface

It is suspected by many authors that most readers pass rapidly over the preface to a technical book so that they can consume its "meatier" portions. However, this book attempts to do a particular job in a special way, and the reader is strongly advised to read this preface to increase the usefulness of the book.

The last text on superalloys appeared in 1959. It was *The Nimonic Alloys* by W. Betteridge of Great Britain, the only metallurgical reference source for the burgeoning superalloy industry for a dozen years, and it treats but a select group of nickel-base alloys. Many metallurgists have felt that a more modern text, which treats all superalloy systems, is particularly needed. The difficulty has been that most of the appropriate authors run so fast they have not had the time to sit down and do the job.

About 4 years ago it was suggested by Henry Hausner that a useful text might be assembled from the papers and talks presented in a course on superalloys at UCLA. Subsequently, this suggestion developed into the concept that a book be generated from chapters identified with specific superalloy subjects and written by various experts. In this way, a complete and solid book could be generated in approximately 2 years from a relatively diffuse effort.

Thus *The Superalloys* is a carefully edited collection of chapters aimed at providing both the scientific and technical background needed to understand the physical metallurgy of the superalloy systems in use today and introduce at least the basis of their exciting and dynamic processing. Included are compilations of chemistry and properties for reference use by engineers and designers along with appropriate complex phase diagrams for alloy developers.

The "chapter compilation" technique, of course, means that conflicting views may well appear within several pages of each other on a given subject. The reader must understand and accept this. The editors choose to regard this as an advantage. A certain degree of repetition may also appear, which is a disad-

vantage of preparing a book in this fashion. However, considerable effort has been exerted to ensure that such repetition is minimized.

In compiling this book, the needs of both metallurgical and materials engineers and of colleges and universities have been specifically kept in mind. Thus this text can be expected to be useful as a metallurgical textbook in college courses on high-temperature materials, as well as to those working in alloy and process development.

Chromium-base alloys are included in this text. While they crystallize in the body-centered-cubic structure, and thus are not considered "true" superalloys by most metallurgists, chromium alloys are primarily of interest as potential heat engine and turbine components in competition with austenitic superalloys. Thus the editors feel chromium alloys provide an interesting contrast to the austenitic systems to which the balance of the book is devoted.

The chapter authors, primarily to conserve space and "keep the text rolling," have been requested to minimize referencing, using only "critical" or "basic" references. The editors take responsibility for this policy.

Many trademarked alloys appear by name in the text; a table to fully identify the source of these trademarks is included in the book.

Many have contributed to the successful issue of this book. The chapter authors are all well-known in their fields, and their enthusiasm and cooperation in this venture has been outstanding. However, we also have a large group of unsung heroes, equally outstanding superalloy metallurgists who willingly agreed to the less rewarding and time-consuming task of reviewing the various chapters. They are: R. E. Allen, J. Barker, T. F. Berry, G. K. Bhat, W. J. Boesch, T. F. Chase, J. W. Clark, D. Coutsouradis, W. P. Danesi, R. Frazer, R. Herchenroeder, B. F. Kear, D. Killpatrick, M. A. Levinstein, L. W. Lherbier, D. J. Maykuth, D. H. Maxwell, J. Mihalisin, K. R. Olen, F. M. Richmond, E. H. Ross, W. E. Savage, A. U. Seybolt, W. Simmons, R. W. Smashey, D. Sponsellor, K. W. Walker, D. F. Stein, E. W. Vandermolen, P. Viatour, F. J. Wall, J. L. Walter, S. T. Wlodek, D. A. Woodford, and C. S. Wukusick. Importantly, some of the authors would like to acknowledge sponsorship of their work by the United States Air Force and by the National Aeronautics and Space Administration. Particular thanks is due Judy Berard who typed more than seven chapters, in addition to accomplishing a myriad of essential editing chores. The authors' company, General Electric, gave full support to this project; without such excellent cooperation, the compilation of the book would not have been possible.

Oh yes, one last but important item. What is a superalloy? We believe a modified American Society for Metals definition is most appropriate:



A superalloy is an alloy developed for elevated temperature service, usually based on group VIIIA elements, where relatively severe mechanical stressing is encountered and where high surface stability is frequently required.

Chester T. Sims

William C. Hagel

*Schenectady, New York*

*Cincinnati, Ohio*

*April 1972*

CONVERSION TABLE  
FOR  
THE INTERNATIONAL SYSTEM OF UNITS (SI SYSTEM)

To convert		Conversion factor	To convert		Conversion factor
from	to		from	to	
A/dm <sup>2</sup>	A/ft <sup>2</sup>	9.290 30	kW	CV or Ps	1.359 62
A/ft <sup>2</sup>	A/dm <sup>2</sup>	0.107 639	kW	hp	1.341 02
Btu	kJ	1.055 06	lb	kg	0.453 592
Btu/h	W	0.293 071	lbf	N	4.448 22
cal	J	4.186 8	lbf/in <sup>2</sup>	kN/m <sup>2</sup>	6.894 76
cm <sup>2</sup>	in <sup>2</sup>	0.155 000	10 <sup>3</sup> x lbf/in <sup>2</sup>	hbar	0.689 476
cm <sup>3</sup>	in <sup>3</sup>	0.061 023	litres (dm <sup>3</sup> )	UK gal	0.219 969
CV	kW	0.735 499	litres (dm <sup>3</sup> )	US gal	0.264 172
ft	m	0.304 8	m	ft	3.280 84
ft <sup>2</sup>	m <sup>2</sup>	0.092 903	m	yd	1.093 61
ft <sup>3</sup>	m <sup>3</sup>	0.028 216	m <sup>2</sup>	ft <sup>2</sup>	10.763 9
ftlbf	J	1.355 82	m <sup>2</sup>	yd <sup>2</sup>	1.195 99
g	oz(av)	0.035 274	m <sup>3</sup>	ft <sup>3</sup>	35.314 7
g	oz(Troy)	0.032 150	m <sup>3</sup>	yd <sup>3</sup>	1.307 95
g/l	oz/UKgal	0.160 359	miles	km	1.609 34
g/l	oz/USgal	0.133 526	mm	in	0.039 370
hbar	kN/m <sup>2</sup>	1.019 72	N	lbf	0.224 809
hbar	10 <sup>3</sup> x lbf/in <sup>2</sup>	1.450 38	oz (av)	g	28.349 5
hbar	UKtonf/in <sup>2</sup>	0.647 490	oz (Troy)	g	31.103 5
hp	kW	0.745 700	oz (av)/UK gal	g/l	6.236 03
in	mm	25.4	oz (av)/US gal	g/l	7.489 15
in <sup>2</sup>	cm <sup>2</sup>	6.451 6	PS	kW	0.735 499
in <sup>3</sup>	cm <sup>3</sup>	16.387 1	t	UK ton	0.984 207
J	cal	0.238 846	UK gal	litres	4.546 09
J	ftlbf	0.737 562	UK ton	t	1.016 05
J	kgf m	0.101 972	UK tonf	kN	9.964 02
kg	lb	2.204 62	UK tonf/in <sup>2</sup>	hbar	1.544 43
kgf m	J	97.806 65	US gal	litres	3.785 41
kN/m <sup>2</sup>	hbar	0.980 665	W	Btu/h	3.412 14
kJ	Btu	0.947 817	yd	m	0.914 4
km	miles	0.621 371	yd <sup>2</sup>	m <sup>2</sup>	0.836 127
km	UK tonf	0.100 361	yd <sup>3</sup>	m <sup>3</sup>	0.764 555
kN/m <sup>2</sup>	lbf/in <sup>2</sup>	0.145 038			

## PERIODIC SYSTEM OF ELEMENTS

1A	2A	3A	4A	5A	6A	7A	8A	9A	10A	11A	12A	13A	14A	15A	16A	17A	18A	19A	20A	21A	22A	23A	24A	25A	26A	27A	28A	29A	30A	31A	32A	33A	34A	35A	36A	37A	38A	39A	40A	41A	42A	43A	44A	45A	46A	47A	48A	49A	50A	51A	52A	53A	54A	55A	56A	57A	58A	59A	60A	61A	62A	63A	64A	65A	66A	67A	68A	69A	70A	71A	72A	73A	74A	75A	76A	77A	78A	79A	80A	81A	82A	83A	84A	85A	86A	87A	88A	89A	90A	91A	92A	93A	94A	95A	96A	97A	98A	99A	100A	101A	102A	103A	104A	105A	106A	107A	108A	109A	110A	111A	112A	113A	114A	115A	116A	117A	118A	119A	120A	121A	122A	123A	124A	125A	126A	127A	128A	129A	130A	131A	132A	133A	134A	135A	136A	137A	138A	139A	140A	141A	142A	143A	144A	145A	146A	147A	148A	149A	150A	151A	152A	153A	154A	155A	156A	157A	158A	159A	160A	161A	162A	163A	164A	165A	166A	167A	168A	169A	170A	171A	172A	173A	174A	175A	176A	177A	178A	179A	180A	181A	182A	183A	184A	185A	186A	187A	188A	189A	190A	191A	192A	193A	194A	195A	196A	197A	198A	199A	200A	201A	202A	203A	204A	205A	206A	207A	208A	209A	210A	211A	212A	213A	214A	215A	216A	217A	218A	219A	220A	221A	222A	223A	224A	225A	226A	227A	228A	229A	230A	231A	232A	233A	234A	235A	236A	237A	238A	239A	240A	241A	242A	243A	244A	245A	246A	247A	248A	249A	250A	251A	252A	253A	254A	255A	256A	257A	258A	259A	260A	261A	262A	263A	264A	265A	266A	267A	268A	269A	270A	271A	272A	273A	274A	275A	276A	277A	278A	279A	280A	281A	282A	283A	284A	285A	286A	287A	288A	289A	290A	291A	292A	293A	294A	295A	296A	297A	298A	299A	300A	301A	302A	303A	304A	305A	306A	307A	308A	309A	310A	311A	312A	313A	314A	315A	316A	317A	318A	319A	320A	321A	322A	323A	324A	325A	326A	327A	328A	329A	330A	331A	332A	333A	334A	335A	336A	337A	338A	339A	340A	341A	342A	343A	344A	345A	346A	347A	348A	349A	350A	351A	352A	353A	354A	355A	356A	357A	358A	359A	360A	361A	362A	363A	364A	365A	366A	367A	368A	369A	370A	371A	372A	373A	374A	375A	376A	377A	378A	379A	380A	381A	382A	383A	384A	385A	386A	387A	388A	389A	390A	391A	392A	393A	394A	395A	396A	397A	398A	399A	400A	401A	402A	403A	404A	405A	406A	407A	408A	409A	410A	411A	412A	413A	414A	415A	416A	417A	418A	419A	420A	421A	422A	423A	424A	425A	426A	427A	428A	429A	430A	431A	432A	433A	434A	435A	436A	437A	438A	439A	440A	441A	442A	443A	444A	445A	446A	447A	448A	449A	450A	451A	452A	453A	454A	455A	456A	457A	458A	459A	460A	461A	462A	463A	464A	465A	466A	467A	468A	469A	470A	471A	472A	473A	474A	475A	476A	477A	478A	479A	480A	481A	482A	483A	484A	485A	486A	487A	488A	489A	490A	491A	492A	493A	494A	495A	496A	497A	498A	499A	500A	501A	502A	503A	504A	505A	506A	507A	508A	509A	510A	511A	512A	513A	514A	515A	516A	517A	518A	519A	520A	521A	522A	523A	524A	525A	526A	527A	528A	529A	530A	531A	532A	533A	534A	535A	536A	537A	538A	539A	540A	541A	542A	543A	544A	545A	546A	547A	548A	549A	550A	551A	552A	553A	554A	555A	556A	557A	558A	559A	560A	561A	562A	563A	564A	565A	566A	567A	568A	569A	570A	571A	572A	573A	574A	575A	576A	577A	578A	579A	580A	581A	582A	583A	584A	585A	586A	587A	588A	589A	590A	591A	592A	593A	594A	595A	596A	597A	598A	599A	600A	601A	602A	603A	604A	605A	606A	607A	608A	609A	610A	611A	612A	613A	614A	615A	616A	617A	618A	619A	620A	621A	622A	623A	624A	625A	626A	627A	628A	629A	630A	631A	632A	633A	634A	635A	636A	637A	638A	639A	640A	641A	642A	643A	644A	645A	646A	647A	648A	649A	650A	651A	652A	653A	654A	655A	656A	657A	658A	659A	660A	661A	662A	663A	664A	665A	666A	667A	668A	669A	670A	671A	672A	673A	674A	675A	676A	677A	678A	679A	680A	681A	682A	683A	684A	685A	686A	687A	688A	689A	690A	691A	692A	693A	694A	695A	696A	697A	698A	699A	700A	701A	702A	703A	704A	705A	706A	707A	708A	709A	710A	711A	712A	713A	714A	715A	716A	717A	718A	719A	720A	721A	722A	723A	724A	725A	726A	727A	728A	729A	730A	731A	732A	733A	734A	735A	736A	737A	738A	739A	740A	741A	742A	743A	744A	745A	746A	747A	748A	749A	750A	751A	752A	753A	754A	755A	756A	757A	758A	759A	760A	761A	762A	763A	764A	765A	766A	767A	768A	769A	770A	771A	772A	773A	774A	775A	776A	777A	778A	779A	780A	781A	782A	783A	784A	785A	786A	787A	788A	789A	790A	791A	792A	793A	794A	795A	796A	797A	798A	799A	800A	801A	802A	803A	804A	805A	806A	807A	808A	809A	810A	811A	812A	813A	814A	815A	816A	817A	818A	819A	820A	821A	822A	823A	824A	825A	826A	827A	828A	829A	830A	831A	832A	833A	834A	835A	836A	837A	838A	839A	840A	841A	842A	843A	844A	845A	846A	847A	848A	849A	850A	851A	852A	853A	854A	855A	856A	857A	858A	859A	860A	861A	862A	863A	864A	865A	866A	867A	868A	869A	870A	871A	872A	873A	874A	875A	876A	877A	878A	879A	880A	881A	882A	883A	884A	885A	886A	887A	888A	889A	890A	891A	892A	893A	894A	895A	896A	897A	898A	899A	900A	901A	902A	903A	904A	905A	906A	907A	908A	909A	910A	911A	912A	913A	914A	915A	916A	917A	918A	919A	920A	921A	922A	923A	924A	925A	926A	927A	928A	929A	930A	931A	932A	933A	934A	935A	936A	937A	938A	939A	940A	941A	942A	943A	944A	945A	946A	947A	948A	949A	950A	951A	952A	953A	954A	955A	956A	957A	958A	959A	960A	961A	962A	963A	964A	965A	966A	967A	968A	969A	970A	971A	972A	973A	974A	975A	976A	977A	978A	979A	980A	981A	982A	983A	984A	985A	986A	987A	988A	989A	990A	991A	992A	993A	994A	995A	996A	997A	998A	999A	1000A
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**Part One**

# **INTRODUCTION**

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# Chapter 1

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## Superalloy Progress

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Superalloy development in the United States began in the 1930s, prompted by the need for more heat-resistant materials in aircraft engine turbosuperchargers. It has been paced, since the early 1940s, by the increasing demands of advancing gas turbine engine technology. For purposes of classification, we identify three main groups of superalloys: cobalt base, nickel base, and iron base; we consider the nickel-iron-base alloys as a special group within the nickel-base class. Chromium-base alloys are not generally regarded as superalloys, but are included in this book for perspective.

In addition to aircraft, marine, industrial, and vehicular gas turbines, superalloys are now used in space vehicles, rocket engines, experimental aircraft, nuclear reactors, submarines, steam power plants, petrochemical equipment, and other high-temperature applications. The largest use for superalloys, however, is the gas turbine industry. We therefore briefly examine a gas turbine engine to learn its operation, its components, and its materials requirements.

### GAS TURBINES

#### Operation

The gas turbine engine ingests air from the atmosphere, compresses it several times, adds fuel, and burns the mixture, thus producing turbine inlet gases in the temperature range of 1350 to 2500°F (730 to 1370°C). A portion of the high-pressure hot gas steam is used to rotate a turbine section, which in turn drives the compressor. The remaining hot gas is available for useful work, for example, producing thrust in turbojet engines or shaft horsepower in turboshaft engines. In each type of engine, however, there are three main sections: the compressor, the burner, and the turbine, as illustrated in Fig. 1.

**Compressor.** Early gas turbine engines employed radial flow compressors, which were limited to compression ratios of approximately 4 : 1. These are



still used in many small engines. Modern compressors in large engines are of the axial flow configuration, consisting of alternate stages of stationary vanes and rotating blades.\* Incoming air is progressively compressed as it passes through each compressor stage. Compression ratios to approximately 16 : 1 are achieved in current commercial engines and reach 25 : 1 in developmental engines.

**Burner.** Part of the compressed air entering the burner section is mixed with fuel and burned within the combustion chamber, producing gas temperatures greater than 3000°F (1650°C). The remaining compressed air flows around the combustion chamber and through slots in the walls to keep them relatively cool and to mix with the 3000°F (1650°C) combustion products in order to cool the gas to 2000–2400°F (1100–1315°C) before it enters the turbine section.

**Turbine.** Hot gases from the combustors are directed by stationary turbine nozzle guide vanes onto the turbine blade (bucket) airfoils, thus rotating the blade-disk-shaft assembly. The energy extracted from the hot gases is transmitted by the shaft to drive the compressor, thereby sustaining engine operation.

### Materials Requirements

Superalloys are generally used in turbine components operating at temperatures above 1000°F (540°C), which include ducts, cases, and liners, as well as the major components: turbine blades, vanes, disks, and combustion cans. We consider the materials requirements of each of these major components.

**Turbine Blades (Buckets).** Turbine blade airfoils generally experience longitudinal stresses to approximately 20,000 psi and temperatures of 1200–1800°F (650–980°C) in their airfoil section. The blade root, which attaches to the disk, is outside the hot gas path and is exposed to a maximum temperature of approximately 1400°F (760°C) but is subjected to tensile stresses of 40,000–80,000 psi. In addition to these demanding strength requirements, turbine-bucket materials must also have adequate ductility to tolerate creep deformation to resist low-cycle fatigue deformation, and to allow seating of the blade in the disk slot. Since these parts are in contact with high-temperature combustion products of high oxygen content, good oxidation resistance is mandatory. Resistance to surface degradation by hot corrosion is also an important requirement of turbine buckets, particularly in industrial turbines. For our purposes, hot corrosion is defined as a combination of oxidation and reaction with sulfur, sodium, vanadium, and other contaminants, which may be contained in fuels

\*“Blade” is the aircraft term; “bucket” is the industrial term in the turbine section.