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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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 disadvantage 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^2	A/ft^2	9.290 30	kW	CV or Ps	1.359 62
A/ft^2	A/dm^2	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^2	kN/m^2	6.894 76
cm^2	in^2	0.155 000	10^3 x lbf/in^2	hbar	0.689 476
cm^3	in^3	0.061 023	litres (dm^3)	UK gal	0.219 969
CV	kW	0.735 499	litres (dm^3)	US gal	0.264 172
ft	m	0.304 8	m	ft	3.280 84
ft^2	m^2	0.092 903	m	yd	1.093 61
ft^3	m^3	0.028 316	m^2	ft^2	10.763 9
ftlbf	J	1.355 82	m^2	yd^2	1.195 99
g	oz(av)	0.035 274	m^3	ft^3	35.314 7
g	oz(Troy)	0.032 150	m^3	yd^3	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	kfg/mm^2	1.019 72	N	lbf	0.224 809
hbar	10^{3}xlbf/in^2	1.450 38	oz (av)	g	28.349 5
hbar	UKtonf/in^2	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^2	cm^2	6.451 6	PS	kW	0.735 499
in^3	cm^3	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^2	hbar	1.544 43
kgf m	J	9.806 65	US gal	litres	3.785 41
kfg/mm^2	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^2	m^2	0.836 127
kN	UK tonf	0.100 361	yd^3	m^3	0.764 555
kN/m^2	lbf/in^2	0.145 038			

PERIODIC SYSTEM OF ELEMENTS

IA	IIA	IIIA	IVA	VA	VIA	VII	VIII			IB	IIB	IIIB	IVB	VB	VIB	VIIB	0	
1 H 1.008																	2 He 4.003	2
3 Li 6.940	4 Be 9.013											5 B 10.82	6 C 12.010	7 N 14.008	8 O 16.000	9 F 19.00	10 Ne 20.183	2 8
11 Na 22.997	12 Mg 24.32											13 Al 26.98	14 Si 28.06	15 P 30.98	16 S 32.066	17 Cl 35.457	18 A 39.944	2 8 8
19 K 39.10	20 Ca 40.08	21 Sc 45.10	22 Ti 47.90	23 V 50.95	24 Cr 52.01	25 Mn 54.94	26 Fe 55.85	27 Co 58.94	28 Ni 58.69	29 Cu 63.54	30 Zn 65.38	31 Ga 69.72	32 Ge 72.60	33 As 74.91	34 Se 78.96	35 Br 79.916	36 Kr 83.8	2 8 18 8
37 Rb 85.48	38 Sr 87.63	39 Y 88.92	40 Zr 91.22	41 Cb 92.91	42 Mo 95.95	43 Tc (99)	44 Ru 101.1	45 Rh 102.91	46 Pd 106.4	47 Ag 107.88	48 Cd 112.41	49 In 114.82	50 Sn 118.70	51 Sb 121.76	52 Te 127.61	53 I 126.92	54 Xe 131.3	2 8 18 18 8
55 Cs 132.91	56 Ba 137.36	57 *La 138.92	72 Hf 178.5	73 Ta 180.88	74 W 183.86	75 Re 186.31	76 Os 190.2	77 Ir 193.1	78 Pt 195.09	79 Au 197.2	80 Hg 200.61	81 Tl 204.39	82 Pb 207.21	83 Bi 209.0	84 Po 210.0	85 At (210)	86 Rn 222	2 8 18 32 18 8
87 Fr (223)	88 Ra 226.05	89 • Ac 227.0																

REFRACTORY METALS

PRECIOUS METALS

TRANSITION METALS

METALLIC BONDING

COVALENT BONDING TENDENCY

COVALENT (NON-METALLIC) BONDING

RARE GASES

* LANTHANUM SERIES	58 Ce 140.13	59 Pr 140.92	60 Nd 144.27	61 Pm (147)	62 Sm 150.43	63 Eu 152.0	64 Gd 157.26	65 Tb 158.83	66 Dy 162.46	67 Ho 164.94	68 Er 167.2	69 Tm 169.4	70 Yb 173.04	71 Lu 174.99	2 8 18 32 9 2
• ACTINIUM SERIES	90 Th 232.12	91 Pa 231.05	92 U 238.07	93 Np (237)	94 Pu 239.11	95 Am (241)	96 Cm (242)	97 Bk (243)	98 Cf (245)	99 Es (253)	100 Fm (254)	101 Md (256)	102 No (254)	103 Lw (259)	2 8 18 32 32 9 2

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Part One

INTRODUCTION

Chapter 1

Superalloy Progress

ROBERT W. FAWLEY
Williams Research Corp., Walled Lake, Michigan

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 turbo*jet* engines or shaft horsepower in turbo*shaft* 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

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*"Blade" is the aircraft term; "bucket" is the industrial term in the turbine section.