SUPERALLOYS

A Technical Guide

Second
Edition

Matthew J. Donachie
Stephen J. Donachie

ASM
INTERNATIONAL

SUPERALLOYS
A Technical Guide

Second Edition

Matthew J. Donachie
Stephen J. Donachie

ASM
INTERNATIONAL

Materials Park, OH 44073-0002
www.asminternational.org

Preview for: *Superalloys: A Technical Guide* (Second Edition), by Matthew J. Donachie and Stephen J. Donachie, ASM International, 2002
Full digital book available at https://doi.org/10.31399/asm.tb.stg2.9781627082679

Copyright © 2002
by
ASM International®
All rights reserved

No part of this book may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording, or otherwise, without the written permission of the copyright owner.

First printing, March 2002
Second printing, March 2003
Third printing, April 2008
Digital printing, October 2013
Fifth printing, February 2020

Great care is taken in the compilation and production of this Volume, but it should be made clear that NO WARRANTIES, EXPRESS OR IMPLIED, INCLUDING, WITHOUT LIMITATION, WARRANTIES OF MERCHANTABILITY OR FITNESS FOR A PARTICULAR PURPOSE, ARE GIVEN IN CONNECTION WITH THIS PUBLICATION. Although this information is believed to be accurate by ASM, ASM cannot guarantee that favorable results will be obtained from the use of this publication alone. This publication is intended for use by persons having technical skill, at their sole discretion and risk. Since the conditions of product or material use are outside of ASM's control, ASM assumes no liability or obligation in connection with any use of this information. No claim of any kind, whether as to products or information in this publication, and whether or not based on negligence, shall be greater in amount than the purchase price of this product or publication in respect of which damages are claimed. THE REMEDY HEREBY PROVIDED SHALL BE THE EXCLUSIVE AND SOLE REMEDY OF BUYER, AND IN NO EVENT SHALL EITHER PARTY BE LIABLE FOR SPECIAL, INDIRECT OR CONSEQUENTIAL DAMAGES WHETHER OR NOT CAUSED BY OR RESULTING FROM THE NEGLIGENCE OF SUCH PARTY. As with any material, evaluation of the material under end-use conditions prior to specification is essential. Therefore, specific testing under actual conditions is recommended.

Nothing contained in this book shall be construed as a grant of any right of manufacture, sale, use, or reproduction, in connection with any method, process, apparatus, product, composition, or system, whether or not covered by letters patent, copyright, or trademark, and nothing contained in this book shall be construed as a defense against any alleged infringement of letters patent, copyright, or trademark, or as a defense against liability for such infringement.

Comments, criticisms, and suggestions are invited, and should be forwarded to ASM International.

Prepared under the direction of the ASM International Technical Books Committee (2001–2002), Charles A. Parker, Chair.

ASM International staff who worked on this project included Veronica Flint, Manager of Book Acquisitions; Bonnie Sanders, Manager of Production; Jill Kinson, Production Project Manager; and Scott Henry, Assistant Director of Reference Publications.

Library of Congress Cataloging-in-Publication Data
Donachie, Matthew J.
Superalloys: a technical guide / M. Donachie, Jr., S. Donachie.—2nd ed.
p. cm.
Includes bibliographical references and index.
ISBN-13: 978-0-87170-749-9 (print); ISBN-10: 0-87170-749-7 (print)
ISBN: 978-1-61503-064-4 (pdf); ISBN: 978-1-62708-267-9 (electronic)
1. Heat resistant alloys. I. Donachie, S. (Steve) II. Title.
TN700 .D66 2002
6.20.1’617—dc21
2001055227
SAN: 204-7586

ASM International®
Materials Park, OH 44073-0002
www.asminternational.org

Printed in the United States of America

Downloaded from http://dl.asminternational.org/technical-books/monograph/106/bookpreview-pdf/594533
by guest

Contents

Dedication

We wish to dedicate this book to our parents, Viola and Matthew Donachie, and our wives, Cynthia and Martha.

Our father was an outstanding self-taught metallurgist. He worked as an electrician in the steel mills in Motherwell, Scotland, for a short time before emigrating to the United States. "Scottie" to his friends, "Steve" to his family, and "Matthew" to later life acquaintances only, was a long time ASMer and introduced us to the art and science of the metallurgy field. Many an hour was spent by us at Steve's labs in Holyoke, MA as we grew through elementary, junior high, and high school. Metallography was an art to be learned at the master's knee. Photography was a passion. All sorts of improvisations were made in the lab to produce the most wondrous metallurgical results. A patient and thorough man, Steve was most responsible for each of us in turn to choose to become a metallurgist and, eventually, to go on to receive our doctorates in the field.

Vi was responsible for our education for a many a year because Steve was away for weeks at a time during the war years of the 1940s. She made certain that we accomplished our studies and encouraged us at all times. Little did we realize the depths of her own talent until we finally were off to college and discovered that Vi had become a painter on canvas, an architect of elegant enamelware, a ceramist, a weaver of some note, and an occasional judge at competitions. She presided over the Holyoke Woman's Club and, at another time, over the Home Information Center. Yes, we remembered that she crocheted and occasionally knitted when we were younger, and her avid reading and breadth of knowledge of current affairs were remarkable. Still, Vi submerged most of her talents until later years to bring all her children to college and beyond. She was quite a remarkable woman!

The patience and character of many women are legendary, and we would like to hold out the examples of our wives, Cynthia (Steve's wife) and Martha (Matt's wife), who have put up with the workaholic nature of our lives for decades. As we have worked at various tasks over the years, they understood and helped to make it easier for us to complete those tasks. Many an evening was spent without our presence, yet they both have encouraged us. It is to them that we also dedicate this book.

With the help and encouragement of our parents and wives, we learned and, hopefully, practiced intellectual investigation and ethical exploration and exposition of knowledge in our chosen areas of metallurgy. We are truly indebted to all for the ways they have influenced our lives.

"How happy is he born and taught
That serveth not another's will
Whose armour is his honest thought
And simple truth his utmost skill!"

Sir H. Wotton in *The Golden Treasury,* F. T. Palgrave, 1861

Steve
Matt

Preface

The superalloys are, indeed, super. For over 6 decades now, they have provided the most reliable and cost effective means of achieving high operating temperature and stress conditions in aircraft and, now, industrial gas turbines. They have resisted all efforts to reduce their importance and decrease the volume of use. Instead, superalloys continue in wide use in the gas turbine field and may well begin to see even more volume of use in other fields. Superalloys now find application in such diverse fields as oil equipment and biomedical implants. As we move through the first decade of the twenty-first century, superalloys seem secure. To be sure, advances in alloy chemistry are not so easy to achieve any more, but it is being done. Surface modification, partly through the application of coating technology, has extended the useful temperature range of alloys concurrent with the introduction of directional structures and then single crystals of superalloys. Melting technology is ''head and shoulders'' above that of just 15 years ago!

In the late 40s and 50s, there were some conferences and a few published books catering to the developing field of superalloys. At Special Metals, a new generation of processing was dawning as vacuum melting of commercial alloys became a reality. By the mid 60s, the majority of the alloys in use today, except for the directionally solidified ones, existed. The 60s saw the zenith of superalloy development as columnar grain alloys and single crystals were made feasible, and many polycrystalline alloys were brought to commercial reality. Papers on superalloys at the ASM and AIME meetings became fairly routine. At the end of the decade, an important conference was set into being by a dedicated group of metallurgists representing ASM, AIME, and ASME. The first International Conference on Superalloys was not originally intended to be the nucleus of a long running forum, but it did indeed become that. The conference, known as the Seven Springs Conference after the original and only conference location, has continued from 1968 into the twenty-first century. Some other conferences have been initiated and prospered as well. Some conferences cover only specific alloys; e.g. Inconel 718 and related alloys are the subjects of a continuing series of conference.

ASM was an early leader in the presentation of books on high-temperature behavior of metals. In 1979, ASM published *Source Book on Materials at Elevated Temperatures*, in 1984, the *Superalloys Source Book*, and in 1988, the first edition of *Superalloys: A Technical Guide*. Other books on high temperature behavior/ properties have been published as well by ASM. The continued success of superalloy technology has encouraged us to undertake a total revision of *Superalloys: A Technical Guide*. The new Second Edition contains much more information than the previous edition and has been modified in layout to better accommodate the technical information provided. The text has been completely revised and expanded from that of the previous edition with many additional figures and new and revised tables.

Virtually all technical aspects of superalloys are covered in this edition. The book is not intended to be exhaustive in every respect, but we believe that the reader will find it to be most comprehensive. Chapter 4 in particular is probably the most complete and up-to-date presentation on alloy melting available. Selection of alloys is covered with many suggestions to lead the reader to ask appropriate questions either of her/himself or others in the application or development of superalloys. Furthermore, the relation of properties and microstructure is covered in more detail than in previous books. The Guide has been reviewed for accuracy, but it is possible that errors will have occurred. The writers would appreciate receiving either corrections or suggestions (or both) from readers.

If you are new to the use of superalloys, we would strongly suggest starting with Chapter 1. ‘‘Superalloys for High Temperatures—A Primer’’ will suit the needs of readers who want just a brief introduction to superalloys and cannot spend more time on the subject. If you are knowledgeable in metallurgy but have limited knowledge of superalloys, you might wish to start with Chapter 3, ‘‘Understanding Superalloy Metallurgy,’’ before proceeding to one of the specialized chapters for more in-depth information. It is most likely that your immediate needs can be satisfied by perusing this book. However, on completing appropriate chapters, you may wish to pursue reading from one of the references listed in Appendix B.

The writers wish to thank all those who contributed to this book, including the many contributors to other ASM books and the *ASM Handbook* series. We extend our special thanks to John Marcin and Joe Goebel who extensively reviewed Chapters 5 and 13 respectively. This book is the product of the authors’ experience in superalloys, totaling close to 60 years between them, the authors’ personal biases, their technical files, and the extensive resources of ASM International. We particularly would like to thank Veronica Flint, retired from ASM International, for her encouragement to pursue this work and for her perseverance over the several years as the material made its way into electronic and now hard copy form. Veronica Flint and Matt have worked on several past ASM books. It was always been a pleasure to work with Veronica and was especially so on this significant update of an important technical field. The successful publication of this Second Edition is a tribute once more to the dedication of ASM International to providing the greatest access to materials information for the widest possible audience.

MJD
mattd@monad.net
SJD
sdonachie@specialmetals.com
October 2001

Chapter 1

Superalloys for High Temperatures—a Primer

How and When to Use This Chapter

It is always difficult to locate concise but precise information on a subject. Executives and managers, particularly in industries using few superalloys, often need just basic information with the least extraneous or amplifying data. Purchasing agents or communications experts need a modest knowledge base to do their jobs more appropriately. The engineer may need more detail but still just a quick refresher about alloy types and design to start. The ability to lay hands on enough practical information to solve problems or answer questions about the superalloys is the basis for this book. The ability to know enough to ask questions and/or delve further into the superalloy field is the basis for this chapter!

The primer provided in this chapter supports such needs as those described previously by providing a concise overview of the major topics considered in the book, starting with a little history and then a statement about the nature of superalloys. This primer introduces the reader simply and directly to the wide variety of topics that must be considered in the application of superalloys. As for the book, whether the user is familiar with basic superalloy metallurgy or is a complete novice, this book provides a single-volume approach to the subject of superalloys. Theory is kept to a minimum, with practical knowledge stressed.

If you are new to the subject, start with this primer; it may be all that you need. If you are somewhat or strongly knowledgeable in the field, check the table of contents and index for valuable insights into what you can find in each succeeding chapter.

Some History

Designers have long had a need for stronger, more corrosion-resistant materials for high-temperature applications. The stainless steels, developed and applied in the second and third decades of the 20th century, served as a starting point for the satisfaction of high-temperature engineering requirements. They soon were found to be limited in their strength capabilities. The metallurgical community responded to increased needs by making what might be termed “super-alloys” of stainless varieties. Of course, it was not long before the hyphen was dropped and the improved iron-base materials became known as superalloys. Concurrently, with the advent of World War II, the gas turbine became a high driver for alloy invention or adaptation. Although patents for aluminum and titanium additions to Nichrome-type alloys were issued in the 1920s, the superalloy industry emerged with the adaption of a cobalt alloy (Vitallium, also known as Haynes Stellite 31) used in dentistry to satisfy high-temperature strength requirements of aircraft engines. Some nickel-chromium alloys (the Inconels and Nimonics), based more or less, one might say, on toaster wire (Nichrome, a nickel-chromium alloy developed in the first decade of the 20th century) were also available. So, the race was on to make superior metal alloys available for the insatiable thirst of the designer for more high-temperature strength capability. It continues yet!

What Are Superalloys and What Can You Do to Them?

Superalloys are nickel-, iron-nickel-, and cobalt-base alloys generally used at temperatures above about 1000 °F (540 °C). The iron-nickel-base superalloys such as the popular alloy IN-718 are an extension of stainless steel technology and generally are wrought. Cobalt-base and nickel-base superalloys may be wrought or cast, depending on the application/composition involved.

A large number of alloys have been invented and studied; many have been patented. However, the many alloys have been winnowed down over the years; only a few are extensively used. Alloy use is a function of industry (gas turbines, steam turbines, etc.). Not all alloys can be mentioned; examples of older and newer alloys are used to demonstrate the physical metallurgy response of superalloy systems (see Chapters 3 and 12). Figure 1.1 compares stress-rupture behavior of the three alloy classes (iron-nickel-, nickel-, and cobalt-base). A representative list of superalloys and compositions, emphasizing alloys developed in the United States, is given in Tables 1.1 and 1.2.

Appropriate compositions of superalloys can be forged, rolled to sheet, or otherwise produced in a variety of shapes. The more highly alloyed compositions normally are processed as castings. Fabricated structures can be built up by welding or brazing, but many highly alloyed compositions containing a large amount of hardening phase are difficult to weld. Properties can be controlled by adjustments in composition and by processing (including heat treatment), and excellent elevated-temperature strengths are available in finished products.

A Short Review of the High-Temperature Strength of Metals

At ordinary temperatures, the strengths of most metals are measured in terms of short-time properties such as yield strength or ultimate strength. However, when temperatures rise, particularly to temperatures (on an absolute temperature scale) of about 50% of the melting point/range for an alloy, strengths must be reckoned in terms of the time over which they are measured. Thus, if a metal is subjected to a load considerably less than the load (stress) that would break it at room temperature, but is at a high temperature, then the metal will begin to extend with time at load.

This time-dependent extension is called creep and, if allowed to continue long enough, will lead to fracture (or rupture, as it is called). Thus the creep strength of a metal or its rupture strength (technically called creep-rupture strength but more commonly called stress-rupture strength) or both are necessary components of understanding its mechanical behavior just as much as are the customary yield and ultimate strengths. Similarly, the fatigue (cyclic) capability will be reduced. So, to fully validate the capability of a metal alloy, dependent on application temperature and load, it may be necessary to provide yield and ultimate strengths, creep strengths, stress-rupture strengths, and appropriate fatigue strengths. Related mechanical properties such as dynamic modulus, crack growth rates, and fracture toughness also may be required. Appropriate physical properties such as thermal expansion coefficient, density, and so on complete the property list.

Basic Metallurgy of Superalloys

Iron, nickel, and cobalt are generally face-centered cubic (fcc-austenitic) in crystal structure when they are the basis for superalloys. However, the normal room-temperature structures of iron and cobalt elemental metals are not fcc. Both iron and cobalt undergo transformations and become fcc at high temperatures or in the presence of other elements alloyed with iron and cobalt. Nickel, on the other hand, is fcc at all temperatures. In superalloys based on iron and cobalt, the fcc forms of these elements thus are generally stabilized by alloy element additions, particularly nickel, to provide the best properties.

The upper limit of use for superalloys is not restricted by the occurrence of any allotropic phase transformation reactions but is a function of incipient melting temperatures of alloys and dissolution of strengthening

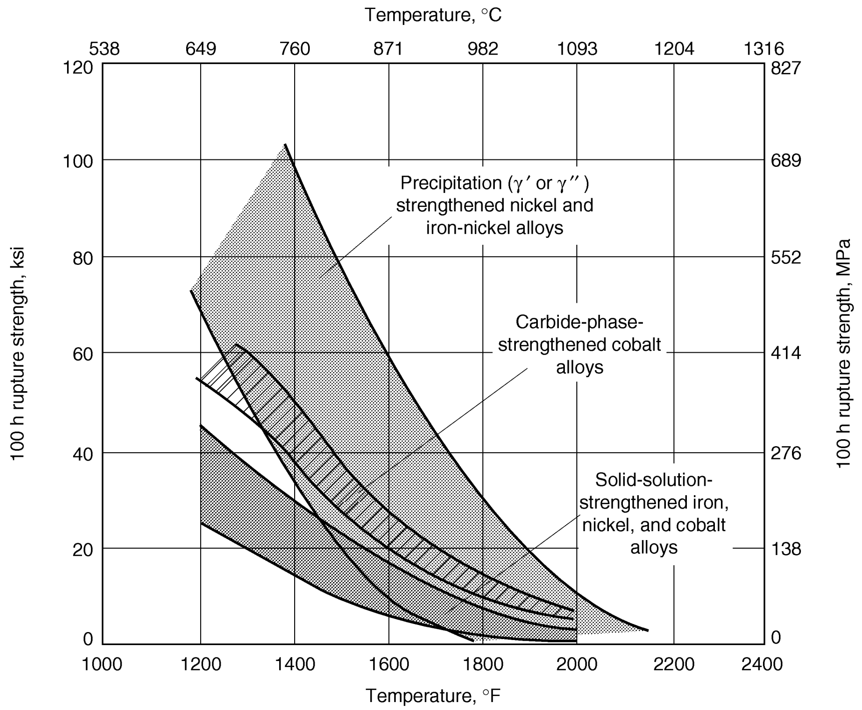

Fig. 1.1 Stress-rupture strengths of superalloys

phases. Incipient melting is the melting that occurs in some part of the alloy that, when solidified, is not at equilibrium composition and thus melts at a lower temperature than that at which it might otherwise melt. All alloys have a melting range, so melting is not at a specific temperature even if there is no nonequilibrium segregation of alloy elements. Superalloys are strengthened not only by the basic nature of the fcc matrix and its chemistry but also by the presence of special strengthening phases, usually precipitates. Working (mechanical deformation, often cold) of a superalloy can also increase strength, but that strength may not endure at high temperatures.

Some tendency toward transformation of the fcc phase to stable lower-temperature phases occasionally occurs in cobalt-base superalloys. The austenitic fcc matrices of superalloys have extended solubility for some alloying additions, excellent ductility, and (iron-nickel- and nickel-base superalloys) favorable characteristics for precipitation of uniquely effective strengthening phases.

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

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

Table 1.1 Nominal compositions of wrought superalloys

Alloy	Composition, %										
	Cr	Ni	Co	Mo	W	Nb	Ti	Al	Fe	C	Other
Solid-solution alloys											
Iron-nickel-base											
Alloy N-155 (Multimet)	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	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
I9-9 DL	19.0	9.0	. . .	1.25	1.25	0.4	0.3	. . .	66.8	0.30	1.10 Mn, 0.60 Si
Incoloy 800	21.0	32.5	. . .	. . .	. . .	. . .	0.38	0.38	45.7	0.05	. . .
Incoloy 800H	21.0	33.0	. . .	. . .	. . .	. . .	. . .	. . .	45.8	0.08	. . .
Incoloy 800HT	21.0	32.5	. . .	. . .	. . .	. . .	0.4	0.4	46.0	0.08	0.8 Mn, 0.5 Si, 0.4 Cu
Incoloy 801	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	22.0	55.0	5.0 max	2.0	14.0	. . .	. . .	0.35	3.0 max	0.10	0.015 max B, 0.02 La
Inconel 600	15.5	76.0	. . .	. . .	. . .	. . .	. . .	. . .	8.0	0.08	0.25 Cu
Inconel 601	23.0	60.5	. . .	. . .	. . .	. . .	. . .	1.35	14.1	0.05	0.5 Cu
Inconel 617	22.0	55.0	12.5	9.0	. . .	. . .	. . .	1.0	. . .	0.07	. . .
Inconel 625	21.5	61.0	. . .	9.0	. . .	3.6	0.2	0.2	2.5	0.05	. . .
RA333	25.0	45.0	3.0	3.0	3.0	. . .	. . .	. . .	18.0	0.05	. . .
Hastelloy B	1.0 max	63.0	2.5 max	28.0	. . .	. . .	. . .	. . .	5.0	0.05 max	0.03 V
Hastelloy N	7.0	72.0	. . .	16.0	. . .	. . .	0.5 max	. . .	5.0 max	0.06	. . .
Hastelloy S	15.5	67.0	. . .	15.5	. . .	. . .	. . .	0.2	1.0	0.02 max	0.02 La
Hastelloy W	5.0	61.0	2.5 max	24.5	. . .	. . .	. . .	. . .	5.5	0.12 max	0.6 V
Hastelloy X	22.0	49.0	1.5 max	9.0	0.6	. . .	. . .	2.0	15.8	0.15	. . .
Hastelloy C-276	15.5	59.0	. . .	16.0	3.7	. . .	. . .	. . .	5.0	0.02 max	. . .
Haynes HR-120	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	28.0	37.0	29.0	. . .	. . .	. . .	. . .	. . .	2.0	0.05	2.75 Si, 0.5 Mn
Nimonic 75	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)	20.0	10.0	50.0	. . .	15.0	. . .	. . .	. . .	3.0	0.10	1.5 Mn
Haynes 188	22.0	22.0	37.0	. . .	14.5	. . .	. . .	. . .	3.0 max	0.10	0.90 La
Alloy S-816	20.0	20.0	42.0	4.0	4.0	4.0	. . .	. . .	4.0	0.38	. . .
MP35-N	20.0	35.0	35.0	10.0	. . .	. . .	. . .	. . .	. . .	. . .	. . .
MP159	19.0	25.0	36.0	7.0	. . .	0.6	3.0	0.2	9.0	. . .	. . .
Stellite B	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	15.0	26.0	. . .	1.25	. . .	. . .	2.0	0.2	55.2	0.04	0.005 B, 0.3 V
Discaloy	14.0	26.0	. . .	3.0	. . .	. . .	1.7	0.25	55.0	0.06	. . .
Incoloy 903	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	. . .	38.4	13.0	. . .	. . .	4.7	1.5	0.03	42.0	0.01	0.15 Si
Incoloy 909	. . .	38.0	13.0	. . .	. . .	4.7	1.5	0.03	42.0	0.01	0.4 Si
Incoloy 925	20.5	44.0	. . .	2.8	. . .	. . .	2.1	0.2	29	0.01	1.8 Cu

(continued)

Table 1.1 (continued)

Alloy	Composition, %										
	Cr	Ni	Co	Mo	W	Nb	Ti	Al	Fe	C	Other
Precipitation-hardening alloys (continued)											
Iron-nickel-base (continued)											
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	13.5	26.0	. . .	1.5	. . .	. . .	2.85	0.2	55.8	0.08 max	0.05 B
Nickel-base											
Astroloy	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	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	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	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	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
IN-100	10	60	15	3	. . .	. . .	4.7	5.5	<0.6	0.15	0.06 Zr, 1.0 V
Inconel 102	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	12.5	42.5	. . .	6.0	. . .	. . .	2.7	. . .	36.2	0.10 max	. . .
Inconel 702	15.5	79.5	. . .	. . .	. . .	. . .	0.6	3.2	1.0	0.05	0.5 Mn, 0.2 Cu, 0.4 Si
Inconel 706	16.0	41.5	. . .	. . .	. . .	. . .	1.75	0.2	37.5	0.03	2.9 (Nb + Ta), 0.15 max Cu
Inconel 718	19.0	52.5	. . .	3.0	. . .	5.1	0.9	0.5	18.5	0.08 max	0.15 max Cu
Inconel 721	16.0	71.0	. . .	. . .	. . .	. . .	3.0	. . .	6.5	0.4	2.2 Mn, 0.1 Cu
Inconel 722	15.5	75.0	. . .	. . .	. . .	. . .	2.4	0.7	7.0	0.04	0.5 Mn, 0.2 Cu, 0.4 Si
Inconel 725	21.0	57.0	. . .	8.0	. . .	3.5	1.5	0.35 max	9.0	0.03 max	. . .
Inconel 751	15.5	72.5	. . .	. . .	. . .	1.0	2.3	1.2	7.0	0.05	0.25 max Cu
Inconel X-750	15.5	73.0	. . .	. . .	. . .	1.0	2.5	0.7	7.0	0.04	0.25 max Cu
M-252	19.0	56.5	10.0	10.0	. . .	. . .	2.6	1.0	<0.75	0.15	0.005 B
MERL-76	12.4	54.4	18.6	3.3	. . .	1.4	4.3	5.1	. . .	0.02	0.35 Hf, 0.06 Zr
Nimonic 80A	19.5	73.0	1.0	. . .	. . .	. . .	2.25	1.4	1.5	0.05	0.10 max Cu
Nimonic 90	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
C-263	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	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
Rene 41	19.0	55.0	11.0	10.0	. . .	. . .	3.1	1.5	<0.3	0.09	0.01 B
Rene 88	16	56.4	13.0	4	4	0.7	3.7	2.1	. . .	0.03	0.03 Zr
Rene 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
Rene 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	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
Udimet 720	18	55	14.8	3	1.25	. . .	5	2.5	. . .	0.035	0.03 Zr
Udimet 720LI	16	57	15.0	3	1.25	. . .	5	2.5	. . .	0.025	0.03 Zr
Unitemp AF2-1DA	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	19.5	57.0	13.5	4.3	. . .	. . .	3.0	1.4	2.0 max	0.07	0.006 B, 0.09 Zr

Table 1.2 Nominal compositions of cast superalloys

Alloy designation	Nominal composition, %											
	C	Ni	Cr	Co	Mo	Fe	Al	B	Ti	Ta	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	. . .
CMSX-4	. . .	bal	6.5	9	0.6	. . .	5.6	. . .	1.0	6.5	6	. . .	
CMSX-6	. . .	bal	10	5	3	. . .	4.8	. . .	4.7	2	. . .	. . .	
CMSX-10	. . .	bal	1.8–4.0	1.5–9.0	0.25–2.0	. . .	5.0–7.0	. . .	0.1–1.2	7.0–10.0	3.5–7.5	. . .	
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	. . .	. . .
PWA 1484	. . .	bal	5	10	2	. . .	5.6	. . .	. . .	9	6	. . .	
Rene 41	0.09	55	19	11.0	10.0	. . .	1.5	0.01	3.1	. . .	. . .	. . .	. . .
Rene 77	0.07	58	15	15	4.2	. . .	4.3	0.015	3.3	. . .	. . .	0.04	. . .
Rene 80	0.17	60	14	9.5	4	. . .	3	0.015	5	. . .	4	0.03	. . .
Rene 80 Hf	0.08	60	14	9.5	4	. . .	3	0.015	4.8	. . .	4	0.02	0.75 Hf
Rene 100	0.18	61	9.5	15	3	. . .	5.5	0.015	4.2	. . .	. . .	0.06	1 V

(continued)

(a) B-1900 + Hf also contains 1.5% Hf. (b) MAR-M 200 + Hf also contains 1.5% Hf. (c) Designated R' 162 in U.S. patent 5,270,123. Also contains 0.02–0.07% C, 0.003–0.01% B, 0–0.3% Y, and 0–6% Ru.

Table 1.2 (continued)

Alloy designation	Nominal composition, %											
	C	Ni	Cr	Co	Mo	Fe	Al	B	Ti	Ta	W	Zr	Other
Nickel-base (continued)												
Rene 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
RR 2000	. . .	bal	10	15	3	. . .	5.5	. . .	4.0	. . .	. . .	. . .	
SRR 99	. . .	bal	8	5	. . .	. . .	5.5	. . .	2.2	3	10	. . .	
Rene N5	. . .	bal	7	8	2	. . .	6.2	. . .	. . .	7	5	. . .	
Rene N6(c)	. . .	bal	4.25–6	10–15	0.5–2	. . .	5–6.25	. . .	. . .	7–9.25	5–6.5	. . .	
Udimet 500	0.1	53	18	17	4	2	3	. . .	3	. . .	. . .	. . .	. . .
Udimet 700	0.1	53.5	15	18.5	5.25	. . .	4.25	0.03	3.5	. . .	. . .	. . .	. . .
Udimet 710	0.13	55	18	15	3	. . .	2.5	. . .	5	. . .	1.5	0.08	. . .
Waspaloy	0.07	57.5	19.5	13.5	4.2	1	1.2	0.005	3	. . .	. . .	0.09	. . .
WAX-20(DS)	0.20	72	. . .	. . .	. . .	. . .	6.5	. . .	. . .	. . .	20	1.5	. . .
Cobalt-base												
AiResist 13	0.45	. . .	21	62	. . .	. . .	3.4	. . .	. . .	2	11	. . .	0.1 Y
AiResist 213	0.20	0.5	20	64	. . .	0.5	3.5	. . .	. . .	6.5	4.5	0.1	0.1 Y
AiResist 215	0.35	0.5	19	63	. . .	0.5	4.3	. . .	. . .	7.5	4.5	0.1	0.1 Y
FSX-414	0.25	10	29	52.5	. . .	1	. . .	0.010	. . .	. . .	7.5	. . .	. . .
Haynes 21	0.25	3	27	64	. . .	1	. . .	. . .	. . .	. . .	. . .	. . .	5 Mo
Haynes 25; L-605	0.1	10	20	54	. . .	1	. . .	. . .	. . .	. . .	15	. . .	. . .
J-1650	0.20	27	19	36	. . .	. . .	. . .	0.02	3.8	2	12	. . .	. . .
MAR-M 302	0.85	. . .	21.5	58	. . .	0.5	. . .	0.005	. . .	9	10	0.2	. . .
MAR-M 322	1.0	. . .	21.5	60.5	. . .	0.5	. . .	. . .	0.75	4.5	9	2	. . .
MAR-M 509	0.6	10	23.5	54.5	. . .	. . .	. . .	. . .	0.2	3.5	7	0.5	. . .
MAR-M 918	0.05	20	20	52	. . .	. . .	. . .	. . .	. . .	7.5	. . .	0.1	. . .
NASA Co-W-Re	0.40	. . .	3	67.5	. . .	. . .	. . .	. . .	1	. . .	25	1	2 Re
S-816	0.4	20	20	42	. . .	4	. . .	. . .	. . .	. . .	4	. . .	4 Mo, 4 Nb, 1.2 Mn, 0.4 Si
V-36	0.27	20	25	42	. . .	3	. . .	. . .	. . .	. . .	2	. . .	4 Mo, 2 Nb, 1 Mn, 0.4 Si
Wi-52	0.45	. . .	21	63.5	. . .	2	. . .	. . .	. . .	. . .	11	. . .	2 Nb + Ta
X-40 (Stellite alloy 31)	0.50	10	22	57.5	. . .	1.5	. . .	. . .	. . .	. . .	7.5	. . .	0.5 Mn, 0.5 Si

(a) B-1900 + Hf also contains 1.5% Hf. (b) MAR-M 200 + Hf also contains 1.5% Hf. (c) Designated R' 162 in U.S. patent 5,270,123. Also contains 0.02–0.07% C, 0.003–0.01% B, 0–0.3% Y, and 0–6% Ru.

melting-point depressants tend to have incipient melting temperatures equal to or in excess of those of cobalt-base superalloys.

Some Superalloy Characteristics and Facts

- When temperatures go above about 1000 °F (540 °C), ordinary steels and titanium alloys are no longer strong enough for application. Steels also may suffer from enhanced corrosion attack.
- When the highest temperatures (below the melting temperatures, which are about 2200 to 2500 °F (1204 to 1371 °C) for most alloys) must be achieved and strength is the consideration, then nickel-base superalloys are the materials of choice.
- Nickel-base superalloys can be used to a higher fraction of their melting points than just about any other commercially available materials. Refractory metals have higher melting points than superalloys but do not have the same desirable characteristics as superalloys and are much less widely used.
- Cobalt-base superalloys may be used in lieu of nickel-base superalloys, dependent on actual strength needs and the type of corrosive attack expected.
- At lower temperatures, and dependent on the type of strength needs for an application, iron-nickel-base superalloys find more use than cobalt- or nickel-base superalloys.
- Superalloy strength properties are directly related not only to the chemistry of the alloy but also to melting procedures, forging and working processes, casting techniques, and, above all, to heat treatment following forming, forging or casting.
- Iron-nickel-base (sometimes designated nickel-iron-base) superalloys such as IN-718 are less expensive than nickel-base or cobalt-base superalloys.
- Most wrought superalloys have fairly high levels of the metal chromium to provide corrosion resistance. In the cast alloys, chromium was high to start but was significantly reduced over the years in order to accommodate other alloy elements that increased the elevated temperature strength of superalloys. In the superalloys based on nickel, the aluminum content of the alloys increased as chromium decreased. Thus, the oxidation resistance of nickel superalloys remained similar to original levels or even increased. However, resistance to other types of corrosion attack decreased.
- Superalloys have great oxidation resistance, in many instances, but not enough corrosion resistance. For many applications at the highest temperatures, above about 1400 °F (760 °C), as in aircraft turbines, superalloys must be coated. For very long-time applications at temperatures at or above about 1200 °F (649 °C), as in land-based gas turbines, superalloys may have to be coated.
- Coating technology is an integral part of superalloy development and application. Lack of a coating means much less ability to use superalloys for extended times at elevated temperatures.
- Many alloy elements are added to superalloys in minuscule to major amounts, particularly in the nickel-base alloys. Controlled alloy elements could be as many as 14 or so in some alloys.
- Nickel and cobalt as well as chromium, tungsten, molybdenum, rhenium, hafnium, and other elements used in superalloys are often expensive and strategic elements that may vary considerably in price and availability over time.

Applications

The high-temperature applications of superalloys are extensive, including components for aircraft, chemical plant equipment, and petrochemical equipment. Figure 1.2 shows the F119 engine, which is the latest in a series of military engines to power high-performance aircraft. The gas temperatures in these engines in the hot sections (rear areas of the engine) may rise to levels far above 2000 °F (1093 °C). Cooling techniques reduce the actual component metal temperatures to lower levels, and superalloys that can operate at these temperatures are the major components of the hot sections of such engines.

The significance of superalloys in today's commerce is typified by the fact that, whereas in 1950 only about 10% of the total weight of an aircraft gas turbine engine was made of superalloys, by 1985 this figure had risen to about 50%. Table 1.3 lists some current applications of superalloys. It will be noted, however, that not all applications re-

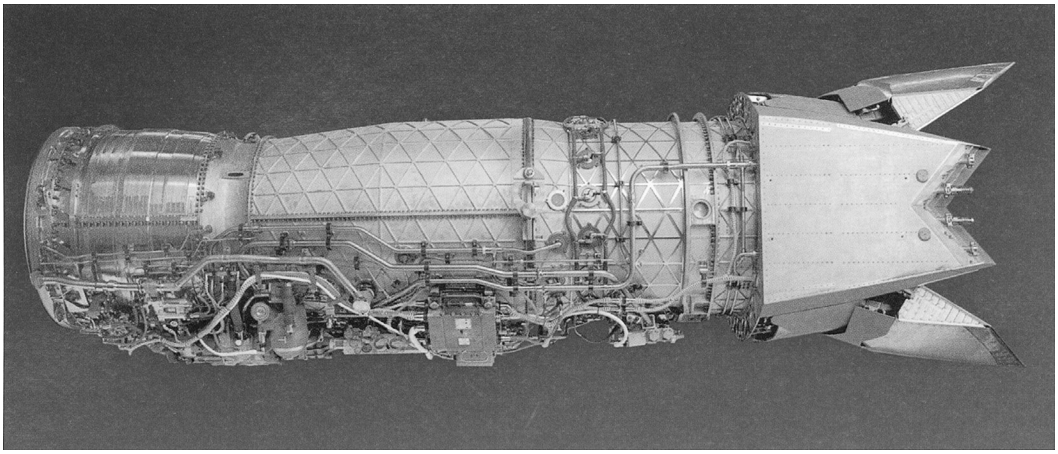

Fig. 1.2 F119 gas turbine engine—a major user of superalloys

Table 1.3 Some Applications of Superalloys

- Aircraft/industrial gas turbine components:
  - Disks
  - Bolts
  - Shafts
  - Cases
  - Blades
  - Vanes
  - Combustors
  - Afterburners
  - Thrust reversers
- Steam turbine power plant components:
  - Bolts
  - Blades
  - Stack-gas reheaters
- Selected automotive components, such as:
  - Turbochargers
  - Exhaust valves
- Metal processing, such as in:
  - Hot work tools and dies
  - Casting dies
- Medical components, such as in:
  - Dentistry
  - Prosthetic devices
- Space vehicle components, such as:
  - Aerodynamically heated skins
  - Rocket-engine parts
- Heat treating equipment:
  - Trays
  - Fixtures
  - Conveyor belts
- Nuclear power systems:
  - Control-rod drive mechanisms
  - Valve stems
  - Springs
  - Ducting
- Chemical and petrochemical industries:
  - Bolts
  - Valves
  - Reaction vessels
  - Piping
  - Pumps

Adapted from *Titanium: A Technical Guide*, 1st ed.

quire elevated-temperature strength capability. Their high strength coupled with corrosion resistance have made certain superalloys standard materials for biomedical devices. Superalloys also find use in cryogenic applications.

What to Look for in This Book

The text provides those who desire it a very complete understanding of superalloys. The chapters “Selection of Superalloys,” “Understanding Superalloy Metallurgy,” “Structure/Property Relationships,” plus “Corrosion and Protection of Superalloys” enhance ability to make design decisions on superalloy use.

For those involved in processing the superalloys, virtually all process operations are included, starting with a very comprehensive look at the initial formulation of superalloys in the chapter “Melting and Conversion.” Subsequently, the gamut of operations is covered from casting to machining and finishing.

If you are experiencing problems with superalloys, reference to the chapters mentioned in the first paragraph of this section is in order. If failures are occurring, check the chapter “Failure and Refurbishment.”

For those desiring a little retrospective look at the current state of superalloy applications and potential future directions, the chapter “Superalloys—Retrospect and Future Prospects” may be of interest.

Preview for: *Superalloys: A Technical Guide* (Second Edition), by Matthew J. Donachie and Stephen J. Donachie, ASM International, 2002
Full digital book available at https://doi.org/10.31399/asm.tb.stg2.9781627082679

Appendix C: Other Sources

Selected References

General

- J.R. Davis, Ed., *Nickel, Cobalt, and Their Alloys*, ASM International, 2001

- M.J. Donachie and S.J. Donachie, Superalloys, *Metals Handbook Desk Edition*, 2nd ed., ASM International, 1999, p 394–414 doi: 10.31399/asm.hb.mhde2.a0003120

- D. Furrer and H. Fecht, Ni-Base Superalloys for Turbine Disks, *J. Met.*, Vol 51 (No. 1), 1999, p 14–17 doi: 10.1007/s11837-999-0005-y

- J.R. Davis, Ed., *Heat-Resistant Materials*, ASM International, 1997

- K.P. Rohrbach, Trends in High-Temperature Alloys, *Adv. Mater. Process.*, Vol 148 (No. 10), 1995, p 37–40

- ASM Handbook, 10th ed., ASM International, various dates, with a wide range of information on all facets of heat-resistant materials and superalloys, from chemistry to processing, microstructure to properties. For example, see chapters in *Properties and Selection: Irons, Steels, and High-Performance Alloys*, Vol 1, 1990

- G.Y. Lai, *High-Temperature Corrosion of Engineering Alloys*, ASM International, 1990

- E.F. Bradley, Ed., *Superalloys: A Technical Guide*, 1st ed., ASM International, 1988

- C.T. Sims, N.S. Stoloff, and W.C. Hagel, Ed., *Superalloys II*, Wiley, 1987

- M.J. Donachie, Ed., *Superalloys Source Book*, American Society for Metals, 1984

- W. Betteridge and J. Heslop, Ed., *The Nimonic Alloys*, 2nd ed., Crane, Russak, and Co., 1974

- C.T. Sims and W.C. Hagel, Ed., *The Superalloys*, Wiley, 1972

- C.P. Sullivan, M.J. Donachie, and F.R. Morral, *Cobalt-Base Superalloys—1970*, Cobalt Information Center, Brussels, 1970

- C.A. Crawford, *Age-Hardenable Nickel-Chromium Alloys*, The International Nickel Co., 1959 (rare)

- The proceedings of a series of conferences in the United States published as follows: *Heat-Resistant Materials* and *Heat-Resistant Materials-II*, ASM International, 1991 and 1995, respectively

- 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*, American Institute of Mining, Metallurgical and Petroleum Engineers, 1989)

- The proceedings of a continuing series of conferences in Europe, first held in 1978 and at four 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 four-year intervals thereafter, with emphasis on high-temperature materials (initial proceedings published as follows: *International Symposium on Structural Stability in Superalloys*, Vol I and Vol II, American Institute of Mining, Metallurgical and Petroleum Engineers, New York, 1968)

Microstructure

- SEM Metallography of Superalloys, S.T. Wlodek, Computer-Aided Microscopy and Metallography, *Microstructural Science*, Vol 18, ASM International, 1990, p 407–429

- M.J. Donachie, Phase Extraction and Analysis in Superalloys—Second Summary of Investigations by ASTM Subcommittee E04.91, *J. Test. Eval.*, Vol 6 (No. 3), 1978, p 189–195 doi: 10.1520/JTE10941J

- H.F. Merrick, Precipitation in Nickel-Base Alloys, *Precipitation Processes in Solids*, Metallurgical Society/American Institute of Mining, Metallurgical and Petroleum Engineers, 1978, p 161–190

- J.R. Mihalisin, Phase Chemistry and Its Relation to Alloy Behavior in Several Cast Nickel-Base Superalloys, *Rev. High-Temp. Mater.*, Vol 2, 1974, p 243–260

- M.J. Donachie and O.H. Kriege, Phase Extraction and Analysis in Superalloys—Summary of Investigations by ASTM Committee E-4 Task Group I, *J. Mats.*, Vol 7, 1972, p 269–278

- E. Kohlhaas and A. Fischer, The Metallography of Superalloys, *Prakt. Metallogr.*, Vol 8, 1971, p 3–25

- J.F. Radavich and W.H. Couts, Metallography of the Superalloys, *Rev. High-Temp. Mater.*, Vol 1, 1971, p 55–96

- P.S. Kotval, The Microstructure of Superalloys, *Metallography,* Vol 1, 1969, p 251–285 doi: 10.1016/0026-0800(69)90038-X

- G.P. Sabol and R. Stickler, Microstructure of Nickel-Base Superalloys, *Phys. Status Solidi*, Vol 35, 1969, p 11–52 doi: 10.1002/pssb.19690350102

- J.L. Johnson and M.J. Donachie, Jr., "Microstructure of Precipitation Strengthened Nickel-Base Superalloys," *Report System Paper C 6-18.1*, American Society for Metals, 1966

Properties and Microstructure

- L. Garimella *et al.*, Fatigue Behaviour in Nickel-Based Superalloys, *J. Met.*, Vol 51 (No. 7), 1999, p 67–71 doi: 10.1007/BF02914771

- J.F. Radavich, The Physical Metallurgy of Cast and Wrought Alloy 718, *Superalloy 718—Metallurgy and Applications,* American Institute of Mining, Metallurgical and Petroleum Engineers, 1989, p 229–240

- R.L. Dreshfield, Understanding Single-Crystal Superalloys, *Met. Prog.*, Vol 130 (No. 2), 1986, p 43–46

- P.N. Quested and S. Ogersby, Mechanical Properties of Conventionally Cast, Directionally Solidified, and Single-Crystal Superalloys, *Mater. Sci. Technol.*, Vol 2 (No. 5), 1986, p 461–475 doi: 10.1179/026708386790328641

- M.J. Donachie, Relationship of Properties to Microstructure in Superalloys, *Superalloys Source Book*, American Society for Metals, 1984, p 102–111

- A.K. Jena and M.C. Chaturvedi, The Role of Alloying Elements in the Design of Nickel-Base Superalloys, *J. Mater. Sci.*, Vol 19, 1984, p 3121–3139 doi: 10.1007/BF00549796

- S.D. Antolovich and N. Jayaraman, The Effect of Microstructure on the Fatigue Behavior of Ni-Base Superalloys, *Fatigue: Environment and Temperature Effects*, Plenum Press, 1983, p 119–144 doi: 10.1007/978-1-4899-1736-2_7

- S.D. Antolovich and J.E. Campbell, Fracture Properties of Superalloys, *Application of Fracture Mechanics for Selection of Metallic Structural Materials*, ASM International, 1982, p 253–310

- M.J. Donachie, Overheating, Creep and Alloy Stability, *Properties and Selection: Stainless Steels, Tool Materials, and Special-Purpose Metals*, Vol 3, Metals Handbook, American Society for Metals, 1980, p 220–229

- R.T. Holt and W. Wallace, Impurities and Trace Elements in Nickel-Base Superalloys, *Int. Met. Rev.*, Vol 21, 1976, p 1–24

Preview for: *Superalloys: A Technical Guide* (Second Edition), by Matthew J. Donachie and Stephen J. Donachie, ASM International, 2002
Full digital book available at https://doi.org/10.31399/asm.tb.stg2.9781627082679

- D.A. Woodford and D.F. Mowbray, Effect of Material Characteristic on Thermal Fatigue of Cast Superalloys: A Review, *Mater. Sci. Eng.*, Vol 16, 1974, p 5–45 doi: 10.1016/0025-5416(74)90135-9

- C.P. Sullivan and M.J. Donachie, a series of review articles on nickel-base, cobalt-base, and iron-nickel-base superalloys in *Met Eng. Q.*, Vol 7 (No. 2), 1967, p 36–45; Vol 9 (No. 2), 1969, p. 16–29; Vol 11 (No. 4), 1971, p 1–11

- R.F. Decker, Strengthening Mechanisms in Nickel-Base Alloys, *Steel Strengthening Mechanisms*, Climax Molybdenum, Greenwich, CT, 1970, p 147–170

- M. Gell *et al.*, The Fatigue Strength of Nickel-Base Alloys, *Achievement of High Fatigue Resistance*, STP 467, ASTM, 1970, p 113–153 doi: 10.1520/STP26842S

- C.T. Sims, A series of review articles in *J. Met.*, Vol 18, 1966, p 1119–1134 doi: 10.1007/BF03378505; Vol 21 (No. 12), 1969, p 27–42 doi: 10.1007/BF03378800

Processing: Melting/Ingot Breakdown

- R.M. Forbes Jones and L.A. Jackman, The Structural Evolution of Superalloy Ingots During Hot Working, *J. Met.*, Vol 51 (No. 1), 1999, p 27–31 doi: 10.1007/s11837-999-0007-9

- A. Mitchell, Recent Developments in Specialty Melting Processes, *Mater. Technol.*, Vol 9, 1994, p 201–206 doi: 10.1080/10667857.1994.11785070

- C.H. White, P.M. Williams, and M. Morley, Cleaner Superalloys via Improved Melting Practices, *Adv. Mater. Process.*, Vol 137 (No. 4), 1990, p 53–57

- L.A. Jackman, G.E. Maurer, and S. Widge, White Spots in Superalloys, *Superalloy 718—Metallurgy and Applications*, American Institute of Mining, Metallurgical and Petroleum Engineers, 1989, p 153–166

- G.E. Maurer, Primary and Secondary Melt Processing—Superalloys, *Superalloys, Supercomposites, and Superceramics*, Academic Press, 1989, p 49–97 doi: 10.1016/B978-0-12-690845-9.50009-9

- J.W. Pridgeon, F.N. Darmara, J.S. Huntington, and W.H. Sutton, Principles and Practices of Vacuum Induction Melting and Vacuum Arc Remelting, *Metallurgical Treatises*, American Institute of Mining, Metallurgical and Petroleum Engineers, 1981, p 261–276

Processing: Forging/Powder Metallurgy

- N.A. Wilkinson, Forging of 718—the importance of T.M.P., *Superalloy 718—Metallurgy and Applications*, American Institute of Mining, Metallurgical and Petroleum Engineers, 1989, p 119–133 doi: 10.7449/1989/Superalloys_1989_119_133

- J.D. Destefani, Clean P/M Superalloys, *Adv. Mater. Process.*, Vol 136 (No. 3), 1989, p 63–66
- H.C. Fiedler *et al.*, The Spray Forming of Superalloys, *J. Met.*, Vol 39 (No. 8), 1987, p 28–33 doi: 10.1007/BF03258605
- J.S. Benjamin, Mechanical Alloying for Preparation of Superalloys, *Advanced High-Temperature Alloys*, American Society for Metals, 1986, p 85–91
- F. Turner and H.S. von Harrach, Press Forging of Superalloys, *Mater. Sci. Technol.*, Vol 2 (No. 7), 1986, p 733–740 doi: 10.1179/mst.1986.2.7.733
- D.C. Wright and D.J. Smith, Forging of Blades for Gas Turbines, *Mater. Sci. Technol.*, Vol 2 (No. 7), 1986, p 742–747 doi: 10.1179/mst.1986.2.7.742
- J.L. Bartos, Review of Superalloy Powder Metallurgy Processing for Aircraft Gas Turbine Applications, *MiCon 78*, STP 672, American Society for Testing of Materials, 1979, p 564–577 doi: 10.1520/STP36890S
- D. Muzyka, Physical Metallurgy and Effects of Process Variables on Microstructure of Wrought Superalloy, *MicOn 78*, STP 672, American Society for Testing of Materials, 1979, p 526–546 doi: 10.1520/STP36888S
- A.J. DeRidder and R. Koch, Forging and Processing of High-Temperature Alloys, *MiCon 78*, STP 672, American Society for Testing of Materials, 1979, p 547–563 doi: 10.1520/STP36889S
- M.J. Blackburn and R.A. Sprague, Production of Components by Hot Isostatic Pressing of Nickel-Base Superalloy Powders, *Met. Technol.*, Vol 4, 1977, p 388–395 doi: 10.1179/030716977803292231
- J.E. Coyne, Microstructural Control in Titanium- and Nickel-Base Forgings: An Overview, *Met. Technol.*, Vol 4, 1977, p 337–345 doi: 10.1179/030716977803292745
- N.A. Wilkinson, Technological Considerations in the Forging of Superalloy Rotor Parts, *Met. Technol.*, Vol 4, 1977, p 346–359 doi: 10.1179/030716977803292637
- D. Muzyka and G.N. Maniar, Microstructure Approach to Property Optimization in Wrought Superalloys, *Metallography—A Practical Tool for Correlating the Structure and Properties of Materials*, STP 557, American Society for Testing of Materials, 1974, p 198–219 doi: 10.1520/STP33334S
- D.R. Muzyka, Controlling Microstructures and Properties of Superalloys via Use of Precipitated Phases, *Met. Eng. Q.*, Vol 11 (No. 4), 1971, p 12–20
- J. Rawson, Effect of Temperature on Forgeability of Some Heat-Resistant Alloys, *Reheating for Hot Working*, Iron and Steel Institute, London, 1968, p 65–69

- Heat-Resistant Superalloys, *Forging Materials and Practices*, Reinhold, 1968, p 254–293

- J.E. Coyne and W.H. Couts, "The Closed-Die Forging of a Nickel-Base Superalloy," Report System Paper C 6-18, American Society for Metals, 1966

- A.J. DeRidder and R.W. Koch, Controlling Variations in Mechanical Properties of Heat-Resistant Alloys During Forging, *Met. Eng. Q.*, Vol 5 (No. 3), 1965, p 61–64

Processing: Investment Casting

- W.J. Molloy, Investment-Cast Superalloys, a Good Investment, *Adv. Mater. Process.*, Vol 138 (No. 4), 1990, p 23–25 and 28–30

- L.E. Dardi *et al.*, Metallurgical Advancements in Investment Casting Technology, *Advanced High-Temperature Alloys—Processing and Properties*, American Society for Metals, 1986, p 25–39

- R.A. Stevens and P.E.J. Flewitt, Hot Isostatic Pressing to Remove Porosity and Creep Damage, *Mater. Eng.*, Vol 3, 1982, p 461–469 doi: 10.1016/0261-3069(82)90112-1

- W.L. Hallerberg, "Superalloy Investment Castings—Processing and Applications," Paper CM71-160, Society of Manufacturing Engineering, 1971

- F.L. VerSnyder and M.E. Shank, The Development of Columnar Grain and Single Crystal High Temperature Materials through Directional Solidification, *Mater. Sci. Eng.*, Vol 6, 1970, p 213–247 doi: 10.1016/0025-5416(70)90050-9

Processing: Machining, Heat Treating, Joining, Refurbishment/Repair

- K.A. Ellison, P. Lowden, and J. Liburdi, Powder Metallurgy Repair of Turbine Components, *J. Eng. Power (Trans. ASME)*, Vol 116, 1994, p 237–242 doi: 10.1115/1.2906799

- W.A. Owczarski, Process and Metallurgical Factors in Joining Superalloys and Other High Service Temperature Materials, *Physical Metallurgy of Metal Joining*, American Institute of Mining, Metallurgical and Petroleum Engineers, 1980, p 166–189

- H.R. Conway, Welding the Nickel Alloys: Dissimilar Metals, High-Temperature Service, *Superalloys Source Book*, American Society for Metals, 1979, p 387–392

- L.A. Jackman, Forming and Fabrication of Superalloys, *Proc. Symposium on Properties of High Temperature Alloys*, The Electrochemical Soc., 1976, p 42–58

- J.A. Burger and D.K. Hanink, Heat Treating Nickel-Base Superalloys, *Met. Prog.*, Vol 92 (No. 1), 1967, p 61–66

• G. Heckman, "*Stabilizing Heat Treatments for Gas Turbine Bucket Alloys*," Paper 67-GT-55, American Society of Mechanical Engineers, March 1967

• C. Olofson *et al.*, *Machining and Grinding of Nickel- and Cobalt-Base Alloys*, Report TM X-53446, National Aeronautics and Space Administration, 1966

• J. Vagi *et al.*, *Joining of Nickel and Nickel-Base Alloys*, Report TM X-53447, National Aeronautics and Space Administration, 1966

Processing: Coatings/Corrosion

• N.S. Bornstein, Reviewing Sulfidation Corrosion—Yesterday and Today, *J. Met.*, Vol 48 (No. 11), 1996, p 37–39 doi: 10.1007/BF03223242

• J.A. Conner and W.B. Connor, Ranking Protective Coatings: Laboratory vs. Field Experience, *J. Met.*, Vol 46 (No. 12), 1994, p 35–38 doi: 10.1007/BF03222662

• S.M. Meier and D.K. Gupta, The Evolution of Thermal Barrier Coatings in Gas Turbine Engine Applications, *J. Eng. Power (Trans. ASME)*, Vol 116, 1994, p 250–257 doi: 10.1115/1.2906801

• S. Besenicar *et al.*, The High Temperature Corrosion Behaviour of Various Alloys and Coatings Under Coal Gasification Conditions, *Mater. High Temp.*, Vol 9 (No. 4), 1991, p 193–227 doi: 10.1080/09603409.1991.11689660

• H. Lammermann and G. Kienel, PVD Coatings for Aircraft Turbine Blades, *Adv. Mater. Process.*, Vol 140, 1991, p 18–23

• S.M. Meier, D.K. Gupta, and K.D. Sheffler, Ceramic Thermal Barrier Coatings for Commercial Gas Turbine Engines, *J Met.*, Vol 43, 1991, p 50–53 doi: 10.1007/BF03220164

• J.R. Nichols and D.J. Stephenson, Applications of Coating Technology and HIP to Advanced Materials Processing, *Mater. High Temp.*, Vol 9, 1991, p 110–120 doi: 10.1080/09603409.1991.11689648

• G.W. Goward and L.W. Cannon, Pack Cementation Coatings for Superalloys: A Review of History, Theory and Practice, *J. Eng. Power (Trans. ASME)*, Vol 110, 1988, p 150–154. doi: 10.1115/1.3240078

• K.N. Strafford *et al.*, Ed., *Coatings and Surface Treatment for Corrosion and Wear Resistance*, Institution of Corrosion Science and Technology, 1988

• G.W. Goward, Low-Temperature Hot Corrosion in Gas Turbines: A Review of Causes and Coatings Therefore, *J. Eng. Power (Trans. ASME)*, Vol 108, 1986, p 421–425 doi: 10.1115/1.3239921

- F.S. Pettit and G.W. Goward, High Temperature Corrosion and Use of Coatings for Protection, *Metallurgical Treatises*, American Institute of Mining, Metallurgical and Petroleum Engineers, 1981, p 603–619

Processing: Modeling

- B.F. Antolovich and M.D. Evans, Predicting Grain Size Evolution of Udimet Alloy 718 During the "Cogging" Process Through Use of Numerical Analysis, *Superalloys 2000*, American Institute of Mining, Metallurgical and Petroleum Engineers, 2000, p 39–47 doi: 10.7449/2000/Superalloys_2000_39_47

- C.A. Dandre *et al.*, Microstructural Evolution of Inconel 718 During Ingot Breakdown: Process Modeling and Validation, *Mater. Sci. Technol.*, Vol 16 (No. 1), 2000, p 14–25 doi: 10.1179/026708300773002627

- N. Saunders, Modeling of Nickel-Base Superalloys, *Adv. Mater. Process.*, Vol 156 (No. 3), 1999, p 29–31

- L. Nastac *et al.*, The Stochastic Modeling of Solidification Structures in Alloy 718 Remelt Ingots, *J. Met.*, Vol 50 (No. 3), 1998, p 30–35 doi: 10.1007/s11837-998-0376-5

- A.L. Purvis *et al.*, Modeling Characteristics for Solidification in Single-Crystal Investment-Cast Superalloys, *J. Met.*, Vol 46 (No. 1), 1994, p 38–41 doi: 10.1007/BF03222535

- J.S. Tu *et al.*, Computer-Aided Development of an Investment Casting Process, *J. Met.*, Vol 45 (No. 10), 1993, p 29–32 doi: 10.1007/BF03222457

- R.I. Ramakrishnan and T.E. Howson, Modeling the Heat Treatment of Superalloys, *J. Met.*, Vol 44 (No. 6), 1992, p 29–32 doi: 10.1007/BF03222251

- P.D. Spilling, Modeling of Aerospace Materials—Not Just A Pretty Picture, *Mater. Sci. Technol.*, Vol 8, 1992, p 145–150 doi: 10.1179/026708392790170423