Superalloys

A Technical Guide

Elihu F. Bradley

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Consulting Editor

ASM INTERNATIONAL™
Metals Park, OH 44073

Preface

The advent of the aircraft turbine engine in the late 1940's and 1950's gave great impetus to high-temperature materials. The concept of the jet engine dictated the need for new construction materials that would combine high-temperature, long-time strength with resistance to elevated temperature corrosion. Throughout the age of the aircraft turbine engine, there has been continuing demand for new materials with improved high-temperature performance, because of the simple fact that the higher the turbine inlet temperature, the higher the thrust that the engine can produce. This demand has fueled a burgeoning superalloy industry throughout the years. It is revealing that the amount of superalloys used in aircraft gas turbine engines has increased from about 10% of the total engine weight at the beginning of the jet age in 1950 to about 50% of the engine weight for modern engines. It is expected that this trend will continue in the future, probably leveling off at about 60% in the 1990's. The use of superalloys has spread beyond aircraft engines as other industries have recognized their high-temperature advantages, but the turbine engine remains the cornerstone of superalloy use.

The physical metallurgy of superalloys is well understood and well documented in the technical literature. It is not the purpose of this book to present a metallurgical treatise on superalloys, because there are many in the current literature. Rather, the intent is to provide the technical community, but not necessarily superalloy specialists, with a current, practical overview or summary of what superalloys are all about. Thus, superalloy types, forms, properties, applicable processes, uses, and problems are covered. The emphasis, therefore, is on practical, not theoretical, information concerning superalloys. Technology, however, is included to support the practical information. Every attempt has been made to express the technical sections in clear, easily understood terms, thus avoiding complex discussions of chemistry and solid-state physics.

It is hoped, then, that this book will be used by producers, fabricators, manufacturers, designers, metallurgists, laboratory personnel, and users of superalloys as a broad, practical reference to superalloy information required for application purposes.

E.F. Bradley

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Chapter 1

Introduction

GENERAL

Many alloys are used at elevated temperatures. These alloys must be able to withstand the deteriorating effect of the service atmosphere, as well as possess sufficient strength for the design condition and have adequate stability to withstand damaging metallurgical structural changes at operating temperature. From the standpoint of resisting oxidation and high-temperature corrosion, the most important alloying element is chromium. It is not surprising that corrosion-resistant steels, stainless steels, nickel-chromium alloys, and superalloys, all of which contain significant amounts of chromium, are used extensively in high-temperature applications.

This book is intended to cover only superalloys, because stainless steels are discussed extensively elsewhere (Ref 1). However, the following brief comments about materials that are used at elevated temperatures other than superalloys are given to help the reader better understand the application role of superalloys. For use at moderate temperatures - less than 540 °C (1000 °F) - and moderate stress, the 12% Cr corrosion-resistant steels are satisfactory. Under conditions of somewhat higher stress at the same moderate temperature, the so-called super 12% Cr steels, a versatile group containing in addition to chromium small amounts of molybdenum and/or other strong carbide formers and/or cobalt or nickel, have been used for over 40 years. As the operating temperature is increased, but for conditions of low stress, higher chromium steels, either the ferritic corrosion-resistant or the austenitic stainless steels containing nickel as well as chromium, or nickel-chromium alloys (for example, Nichrome V, containing 20% Cr and 80% Ni), commonly are selected.

For very high operating temperatures, there is increasing interest in the refractory metals of Groups V (vanadium, niobium, and tantalum) and VI (chromium, molybdenum, and tungsten), as well as ceramics. The refractory metals, however, exhibit very poor oxidation resistance, and their use is now restricted to nonoxidizing environments. Ceramics possess insufficient toughness for most structural applications. Elevated temperatures have been a disappointing limitation for titanium ever since its introduction into turbine engines in the middle 1950's. Two reasons for this limitation persist: (*a*) the affinity of titanium for interstitial elements, and (*b*)

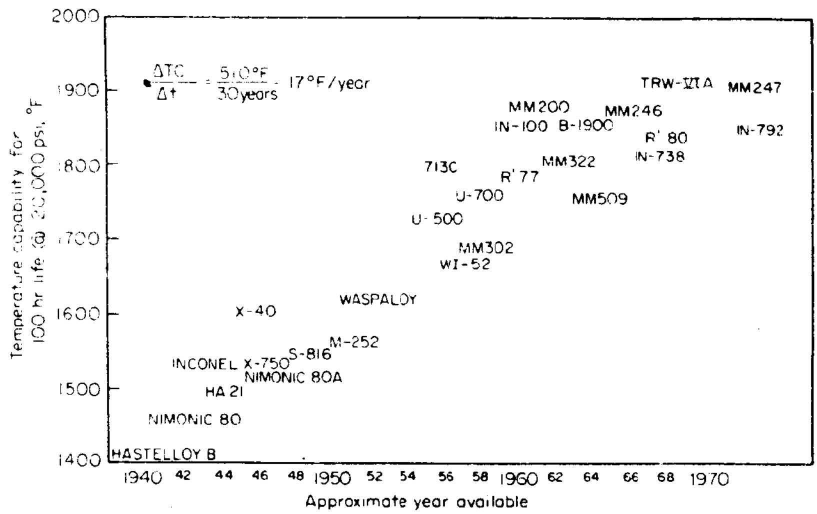

Fig. 1.1 Historical development and typical temperature capability of superalloys

inadequate creep strength at even the moderate temperature level of about 540 °C (1000 °F). Therefore, for the most severe combination of stress and temperature, it remains for the remarkable superalloys to do the job.

WHAT IS A SUPERALLOY?

A superalloy is an alloy developed for elevated temperature service, usually based on Group VIII A elements, where relatively severe mechanical stressing is encountered and where surface stability frequently is required. The term "superalloy" was first used shortly after World War II to describe a group of alloys developed for use in turbosuperchargers and aircraft turbine engines that required high performance at elevated temperatures. These alloys usually consist of various formulations made from the following elements: iron, nickel, cobalt, and chromium, as well as lesser amounts of tungsten, molybdenum, tantalum, niobium, titanium, and aluminum. The most important properties of the superalloys are long-time strength at temperatures above 650 °C (1200 °F) and resistance to hot corrosion and erosion. Many types of alloys fall under the broad coverage of superalloys. These include iron-base alloys containing chromium and nickel, complex iron-nickel-chromium-cobalt compositions, carbide-strengthened cobalt-base alloys, solid-solution-strengthened nickel-base alloys, and precipitation- or dispersion-strengthened nickel-base alloys (Fig. 1.1). Superalloys are used in both the wrought and the cast forms.

Generally, the strengths of the iron-base alloys, the complex iron-nickel-chromium-cobalt alloys, and the nickel-base solid-solution-strengthened alloys are considerably lower than those of the nickel-base second-phase-strengthened and cobalt-base alloys at temperatures above 650 °C (1200 °F). Early iron-base superalloys,

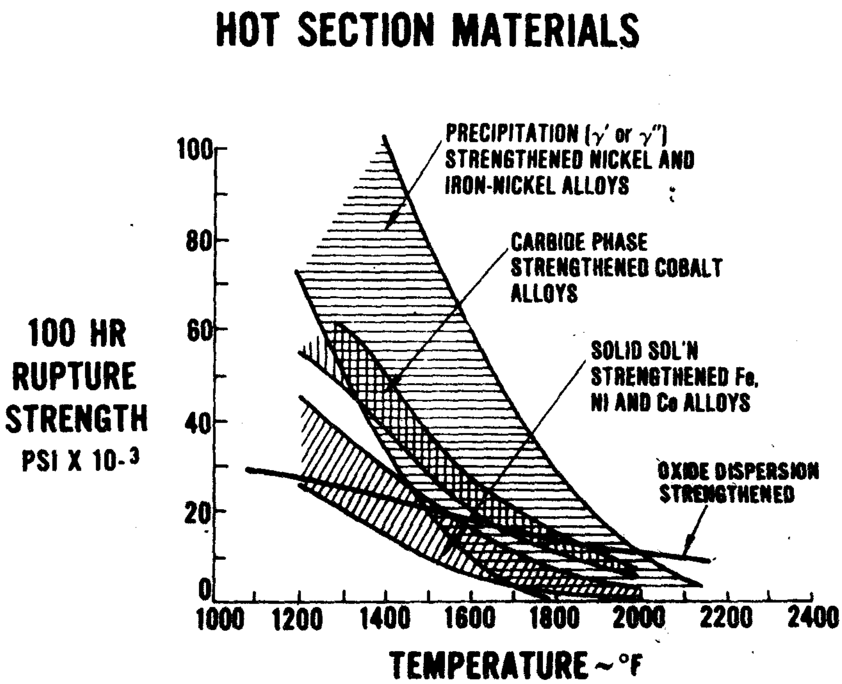

Fig. 1.2 Stress-rupture characteristics of select superalloys

such as 16-25-6 alloy containing 16% Cr, 25% Ni, and 6% Mo, and complex iron-nickel-chromium-cobalt alloys (Fe-20Ni-20Cr-20Co, for example) with small amounts of tungsten and molybdenum, are essentially solid-solution strengthened. Later iron-base alloys, containing small amounts (2 to 3%) of aluminum and titanium, achieved increased high-temperature strength through precipitation of an aluminum-titanium strengthening phase. Because of a melting-point advantage, the cobalt alloys are usually stronger than the nickel alloys at temperatures above 1100 °C (2000 °F). Cast cobalt-base alloys, characterized by a face-centered-cubic (fcc, austenitic) solid-solution matrix and containing complex carbides, have had a successful history as airfoils for gas turbine engines (most turbine vanes and some turbine blades).

One exception to this strength observation is the dispersion-strengthened nickel alloys, utilizing a dispersed-oxide strengthening phase, which exhibit high strength at elevated temperatures, but only moderate strength at intermediate temperatures. The secondary phase persists in the structure of these alloys as a strengthening mechanism throughout the solid state until melting occurs. In contrast, alloys strengthened by precipitation lose the strengthening phase by solution in the solid state at some temperature below the melting point. Dispersion-strengthened alloys are beginning to be used in some gas turbine engine burner applications. Figure 1.2 compares stress-rupture behavior of the various superalloy classes.

Clearly, the nickel-base superalloys strengthened by a secondary precipitated phase are the most complex and, indeed, the most remarkable of all the superalloys. The physical metallurgy of these alloys is subtle, sophisticated, and well understood. The structure consists of an fcc, austenitic solid-solution matrix with a precipitated nickel-aluminum-titanium compound (γ') as the principal strengthening phase. Various carbides, depending on the particular alloy composition and heat treatment, exist as second precipitated phases. These alloys are used in the most demanding applications relative to stress and temperature in gas turbine engines. They have demonstrated remarkably useful strength at the highest fraction of the base metal melting point of any alloy system ever developed.

Castings and Forgings

Castings are intrinsically stronger than forgings at elevated temperatures. The coarse grain size of castings, as compared to fine-grain forgings, favors strength at very high temperatures. In addition, casting compositions can be effectively tailored for high-temperature strength, inasmuch as forgeability characteristics are not a factor. Higher elevated temperature strength can be achieved in the nickel-base, γ'-strengthened superalloys, for example, by lowering the chromium content, but at the expense of hot corrosion resistance. Superalloys of this type, containing only 8 to 12% chromium, may require the use of coatings (such as diffused aluminum) to compensate for the loss in hot corrosion resistance of the alloy. The addition of small amounts of hafnium (1 to 1.5%) causes a marked improvement in the intermediate-temperature ductility of these high-strength nickel superalloy castings. Because of the high-temperature strength advantage, many aircraft gas turbine engines use nickel-base, γ'-strengthened superalloy castings for high-stress, high-temperature turbine blade applications.

Innovation in the casting process also has resulted in improved high-temperature properties. The development of directional solidification involving controlled grain growth, whereby all crystals are aligned in the longitudinal direction, has provided increased high-temperature strength and, in particular, significant improvement in resistance to thermal fatigue.

Wrought Products

The major structural difference between a wrought product and a casting is that wrought products possess a finer grain condition, which is achieved by hot working. Wrought products have better strength and ductility than castings at room-to-moderately high temperatures - about 540 °C (1000 °F). Wrought products, in addition, generally have better fracture and fatigue properties than castings, because defects and large grains are broken up and porosity is healed during the hot working processes. Therefore, for critical structural applications requiring dynamic fracture reliability at these low-to-moderate temperatures, the material choice has favored wrought products.

Powder Metallurgy

The use of metal powders to obtain chemically and metallurgically uniform structures for critical aircraft engine parts is increasing with the advent of high-purity, prealloyed superalloy powders, and the development of suitable shaping techniques, such as isothermal forging and hot isostatic pressing. Another significant development relative to powder cleanliness is inert processing, wherein powder production, collection, and densification are carried out in an inert atmosphere. High-strength, nickel-base superalloys are prone to severe macrosegregation that inhibits successful ingot breakdown. Conceptually, powder metallurgy (P/M) offers a method for overcoming this problem. Because the material is divided into small droplets while it is a homogeneous liquid, the maximum segregation distance is restricted to the size of the solidified droplets.

Production of superalloy powders using rapid solidification technology (RST) is receiving major research attention. In view of the high cooling rate achieved in RST - 1,008,000 °C/s (1,800,000 °F/s) - it may be possible to produce new alloys and microstructures with a high degree of compositional homogeneity and fine microstructure in each spherical powder particle with very narrow and fine size distribution. This could provide a quantum leap in alloy technological potential. The value of these metastable microstructures, however, will be determined by the extent to which the metastability persists during processing and subsequent service.

NEW APPROACHES

Although materials technology has pushed the use of superalloys to temperatures close to their melting points, materials scientists are studying methods for still further advances. Single-crystal components, characterized by the complete absence of grain boundaries, are beginning to be used. Directionally solidified eutectics, wherein aligned whiskers grow from the eutectic phase within a ductile matrix, are emerging as fiber-reinforced alloys (*in situ* composites) of great strength and stability with the promise of even higher temperature capability. New approaches involving P/M and thermomechanical processing may significantly improve strength at intermediate temperatures. The use of P/M technology to disperse oxide particles in γ'-strengthened superalloys has promise of improved high-temperature strength. The combination of composite technology with superalloy metallurgy may provide future turbine blade materials.

APPLICATIONS

The high-temperature applications of superalloys are extensive, including components for aircraft, chemical plant equipment, and petrochemical equipment. The increasing 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 turbojet engine was made of superalloys, by 1985 this figure had risen to about 50%, and it is expected to reach 60% by 1993.

Current applications of superalloys include:

Aircraft and industrial gas turbines:
- Disks
- Bolts
- Shafts
- Cases
- Blades
- Vanes
- Burner cans
- Afterburners
- Thrust reversers

Steam-turbine power plants:
- Bolts
- Blades
- Stack-gas reheaters

Reciprocating engines:
- Turbochargers
- Exhaust valves
- Hot plugs
- Precombustion cups (Riccardo-type diesel)
- Valve-seat inserts

Metal processing:
- Hot work tools and dies
- Cast dies

Medical applications:
- Dentistry
- Prosthetic devices

Space vehicles:
- 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

PRODUCT FORMS

Wrought superalloys are manufactured in all mill forms common to the metal industry. Iron-base, cobalt-base, and nickel-base superalloys are produced conventionally as bar, billet, extrusions, plate,