TITANIUM

A Technical Guide

Second Edition

Matthew J. Donachie, Jr.

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by guest

I wish to dedicate this book to my wife, Martha. She has been with me through many an adventure in this life and has put up with uncounted hours of my toiling on books, lectures and the like.

My life is a homing bird that flies
Through the starry dusk and dew
Home to the heaven of your true eyes
Home, dear heart, to you.

from the poem *My Life is a Bowl*
by May Riley Smith

When my hair shall shade the snowdrift,
And mine eyes shall dimmer grow,
I would lean upon some loved one,
Through the valley as I go.
I would claim of you a promise,
Worth to me a world of gold:
It is only this, my darling,
That you'll love me when I'm old.

from the poem *Will You Love Me When I'm Old*
author unknown

Sing, for faith and hope are high--
None so true as you and I--
Sing the Lover's Litany:
"Love like ours can never die!"

from the poem *Lovers Litany*
by Rudyard Kipling

Matt

ASM International Technical Books Committee (1999-2000)

Contents

Preface

Titanium and its alloys continue to provide excellent service in a variety of industries. As we progress into the twenty-first century, in the sixth decade of titanium's commercial and industrial use, it appears that the industry has matured, but new technology and applications for the metal continue to develop. Despite the utility of titanium and its alloys, the number of books dealing with the metal has been limited. A series of *International Conferences on Titanium,* held periodically since 1968, have provided a focus for research reports while other occasional symposia and articles have contributed to the industrial literature on titanium. ASM International has been a leader in providing coverage of titanium and its alloys and has issued several books, including the first edition of *Titanium: A Technical Guide*.

Titanium: A Technical Guide, Second Edition, is meant to provide the most complete introduction possible to the metal and its alloys through the use of 14 chapters and 11 appendices. The aim has been to condense and review the significant features of the metallurgy and application of titanium and its alloys. The text has been revised and expanded from that of the first edition with many additional figures and new and revised tables. The second edition of the *Guide* not only contains more information than the previous edition, but the book also has been modified to a larger page size to better accommodate the tables provided. All technical aspects of the use of titanium are covered with sufficient metals property data for most users. The *Guide* has been reviewed for accuracy, but it is possible that errors will have occurred. The editor would appreciate receiving either corrections or suggestions from readers.

If you are new to the use of titanium, I would strongly recommend starting with Chapter 1: A Primer on Titanium and Its Alloys. This executive summary of the metal and its uses should suit the needs of readers who require a brief introduction to titanium and who do not have time to devote to more intense study of the subject. If you are knowledgeable in metallurgy and/or materials engineering, or wish more in-depth information, you may prefer to choose from one of the chapter topics or the appendices that is more relevant to your immediate needs. For additional property data, see the ASM book *Materials Property Handbook: Titanium Alloys*.

The editor wishes to thank not only those who contributed to the first edition of *Titanium: A Technical Guide,* but also the many contributors to other ASM books and the *ASM Handbook* series. This book is a product of the editor's experience and personal bias, as well as his technical files. Most of all, however, it is a product of the resources available in the ASM International system. The editor especially would like to thank Veronica Flint of ASM International for her perseverance with him as the material made its way into electronic form. Veronica and I worked together on the first edition of *Titanium: A Technical Guide,* and it has been a pleasure to work with her again on this significant update. Its successful publication is a tribute to the dedication of ASM International to providing access to materials information for the widest possible audience.

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Chapter 1

A Primer on Titanium and Its Alloys

ReadMe.First

IN THE BUSINESS WORLD OF TODAY, the extended treatment offered by many reference books may pose an obstacle to a manager or other person needing to find information on a specific topic in a reasonable time. This is especially true when only an operational understanding of a subject is required. *Titanium: A Technical Guide, Second Edition* addresses the need for a concise printed summary of the most useful information required to understand titanium and its alloys.

Even in a summary volume, there is a need for an overview of the technical aspects of a metal. This primer supports the needs of engineering, management, and other professionals for information on titanium by providing a brief overview of the major topics that are discussed more thoroughly throughout the book. The information in this chapter will maximize the reader's ability to use the volume in the most efficient way and, at the same time, help the reader to glean enough information to satisfy his or her immediate requirements.

After reading the primer, the reader might wish to refer to the Contents and the Index to locate more information about specific topics. Helpful information can also be found in the Glossary (Appendix J) and the list of Symbols (Appendix I).

Why Use Titanium and Its Alloys?

Titanium was discovered in 1790 but not purified until the early 1900s. Moreover, the metal did not become widely used until the second half of the twentieth century. However, titanium now has the accumulated experience of some 50 years of modern industrial practice and design application to support its use. Much of this use has come in military applications in aircraft such as the SR71 (Fig. 1.1) or gas turbine engines (Fig. 1.2). More recent uses have featured such items as golf clubs and bicycles. Titanium has found its niche in many industries, owing to its unique density, corrosion resistance, and relative strength advantages over competing materials such as aluminum, steels, and superalloys. Some significant facts and/or important benefits offered by titanium alloys illustrate the basis for the widespread use of titanium today:

- The density of titanium is only about 60% of that of steel or nickel-base superalloys.
- The tensile strength (as an alloy) of titanium can be comparable to that of lower-strength martensitic stainless and is better than that of austenitic or ferritic stainless. Alloys can have ultimate strengths comparable to iron-base superalloys, such as A286, or cobalt-base alloys, such as L605.
- The commercial alloys of titanium are useful at temperatures to about 538 °C to 595 °C (1000 °F to 1100 °F), dependent on composition. Some alloy systems (titanium aluminides) may have useful strengths above this temperature.
- The cost of titanium, while approximately four times that of stainless steel, is comparable to that of superalloys.
- Titanium is exceptionally corrosion resistant. It often exceeds the resistance of stainless steel in most environments, and it has outstanding corrosion resistance in the human body.

Fig. 1.1 SR71 aircraft: first use of beta alloys in aerospace structures. Courtesy of Lockheed California Co.

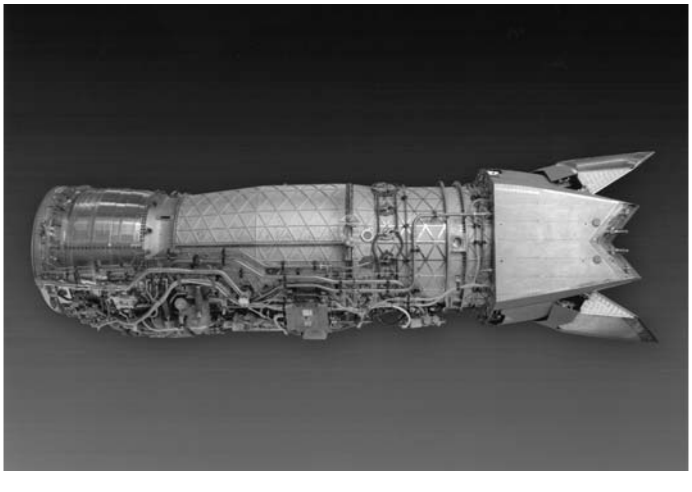

Fig. 1.2 F119 engine by Pratt & Whitney powering the F22 Raptor aircraft

- Titanium may be forged or wrought by standard techniques.
- Titanium is castable, with investment casting the preferred method. (Investment cast titanium alloy structures have a lower cost than conventional forged/wrought fabricated titanium alloy structures.)
- Titanium may be processed by means of P/M technology. (Powder may cost more, yet P/M may offer property and processing improvements as well as an overall cost-savings potential.)
- Titanium may be joined by means of fusion welding, brazing, adhesives, diffusion bonding, and fasteners.
- Titanium is formable and readily machinable, assuming reasonable care is taken.
- Titanium is available in a wide variety of types and forms.

Titanium Metallurgy—A Short Course

Structures in General

The melting point of titanium is in excess of 1660 °C (3000 °F), although most commercial alloys operate at or below 538 °C (1000 °F). Titanium has two elemental crystal structures: in one, the atoms are arranged in a body-centered cubic (bcc) array; in the other, the atoms are arranged in a close-packed hexagonal array (Fig. 1.3). The cubic structure is found only at high temperatures, unless the titanium is alloyed with other elements to maintain the cubic structure at lower temperatures.

The two crystal structures of titanium are commonly known as alpha and beta. Alpha actually refers to any hexagonal titanium, pure or alloyed, while beta denotes any cubic titanium, pure or alloyed. The alpha and beta "structures"—sometimes called systems or types—are the basis for the generally accepted four classes of titanium alloys: alpha, near-alpha, alpha-beta, and beta.

Figure 1.4 schematically shows some effects of alloying elements on structure for representative alloys and classes or subclasses of titanium alloys. The figure also indicates the effects that structures have on some selected properties. The alloy compositions indicated are not meant to be all inclusive but rather to suggest some of the alloys used in titanium alloy design.

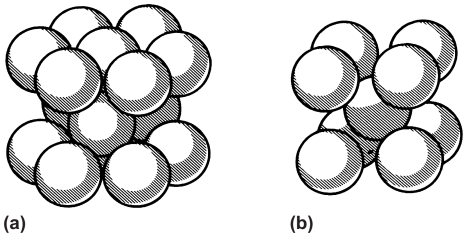

Fig. 1.3 Appearance of crystal structures of titanium at the atomic level. (a) Hexagonal, close packed. (b) Cubic, body centered

More on Structure

Commercially pure (CP) titanium is alpha in structure. Additions of alloying elements to pure titanium produce the range of possible microstructures in titanium alloys.

With sufficient beta-favoring alloy element level, beta phase is produced on heating and transformed during the cooling following high processing. The resulting structures are representative of the alpha-beta alloys.

A variation of alpha alloys recognizes the wide range of alloy chemistry and structure possible within the essentially alpha range. This variation is termed *near-alpha*.

Beta structures generally should be referred to as metastable beta. These are alloys that retain an essentially beta structure on cooling to room temperature.

Titanium aluminides are intermetallic compounds of titanium and aluminum (with one or more additional alloy element provided as well).

Titanium and Titanium Alloy Characteristics

Commercially pure titanium and the alpha and near-alpha titanium alloys generally demonstrate the best general corrosion-resistance qualities. They are the most weldable of the titanium/titanium alloy family.

Pure titanium usually has some amount of oxygen alloyed with it. The strength of CP titanium is affected by the interstitial (oxygen and nitrogen) element content.

Alpha alloys usually have high amounts of aluminum that contribute to oxidation resistance at high temperatures. (Alpha-beta alloys also contain, as the principal element, high amounts of aluminum, but the primary reason is to stabilize the alpha phase.)

Alpha alloys cannot be heat treated to develop higher mechanical properties because they are single-phase alloys. The addition of certain alloying elements to pure titanium en-

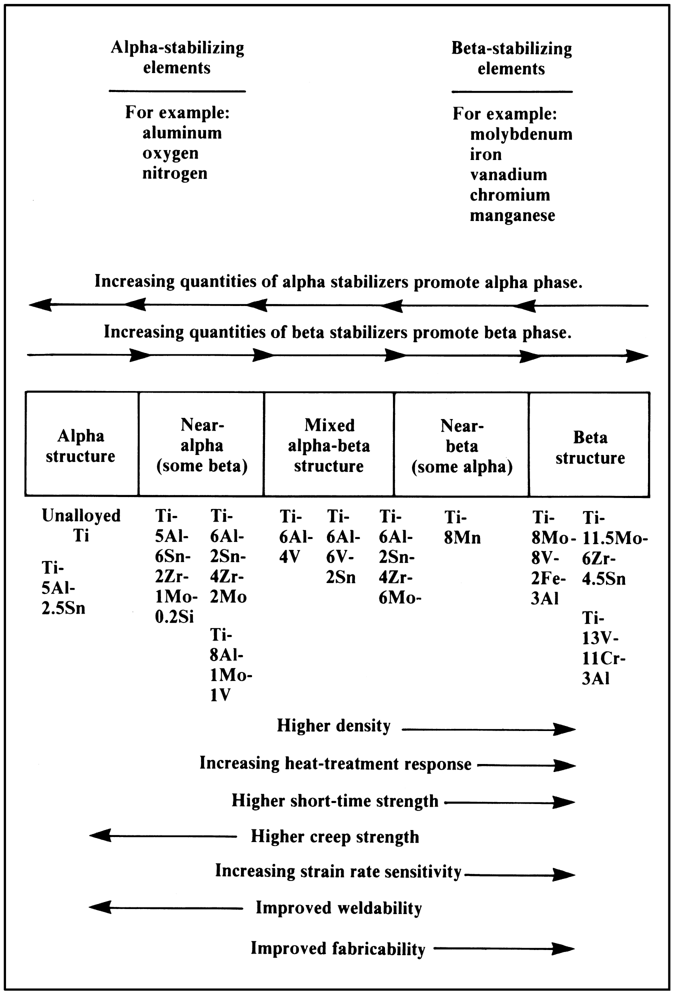

Fig. 1.4 Schematic showing effects of alloy elements on structure and some selected properties (representative alloys noted)

ables the resultant alloys to be heat treated or processed in the temperature range where the alloy is two phase (alpha and beta). The two-phase condition permits the structure to be refined and, by permitting some beta to be retained temporarily at lower temperature, enables optimum control of the microstructure during subsequent transformation when the alloys are "aged" after cooling from the forging or solution heat treatment temperature.

The alpha-beta alloys, when properly treated, have an excellent combination of strength and ductility. They are stronger than the alpha or the beta alloys.

The beta alloys are metastable; that is, they tend to transform to an equilibrium, or balance of structures. The beta alloys generate strength from the intrinsic strength of the beta structure and the precipitation of alpha and other phases from the alloy through heat treatment after processing.

The most significant benefit provided by a beta structure is the increased formability of such alloys relative to the hexagonal crystal structure types (alpha and alpha-beta).

Titanium aluminides differ from conventional titanium alloys in that they are principally chemical compounds alloyed to enhance strength, formability, and so on. The aluminides have higher operational temperatures than conventional titanium, but at higher cost, and generally have lower ductility and formability.

Getting the Most Out of Titanium Alloys

The greatest potential that titanium and titanium alloys can provide in a specific application is realized if a few simple rules of thumb are kept in mind initially before a design is actually begun. Some of the more important guidelines are as follows:

- Wrought titanium alloy products are the more readily available, but castings are close behind. Wrought alloys also have the greatest experience factor. Castings, however, are useful for savings in weight and cost. Cast-plus-HIP (hot isostatic pressed) material can attain comparable operating strength levels to wrought products for most alloys.
- Powder alloys are becoming more accepted. Also, powder processing allows more exotic titanium alloys to be mixed. However, because of the interaction of titanium with interstitial gases such as oxygen and nitrogen, complex powder production techniques are necessary. Consequently, titanium alloy powder may be too expensive for many applications. Furthermore, property levels for powder-processed conventional alloy compositions may not reach expectations. Nevertheless, with powder, there is the built-in, and possibly cost-offsetting, near-net shape (NNS) capability that powder offers. This implies at least a potential for overall lower costs when amortized over the entire project.
- Cast or powder titanium alloys always should be possible candidate materials for structural applications. However, planning for such use should begin during the initial design stage rather than waiting and trying to fit the cast or powder-processed material into a wrought alloy design late in the developmental stages.
- It is wise when making a titanium alloy selection to use the more common alloys unless uncommon properties are absolutely needed. (Ti-6A1-4V clearly has widespread advantages, or else it would not be so commonly used.)
- Handbooks, reference material, and so on all are valuable in design. Numerous handbooks are available (Appendix K provides a selected references list), but there is no substitute for personal contact with a supplier or fabricator. (A partial list of titanium trade organizations, suppliers, and primary metal fabricators appears in Appendix E.)
- Properties that assume unusual forming conditions and/or unrealistic casting or powder processing yields should not be depended on, nor should unusual cooling or heating practices for properties. Cast and powder alloy properties may fall short of the best of wrought alloy properties. Typical properties may be roughly comparable, but data scatter in cast (and possibly in powder) products could result in lower design minimums. If a design admits of no flexibility with respect to property level realization, the design may be irreversibly compromised later.
- Aerospace specifications provide for the best properties and performance. When using titanium in noncritical applications, less stringent specifications should be chosen, where possible, to save money and time.

Some Thoughts about the Future

The dynamic nature of industry as well as developments of a political nature can and will continue to affect the future of the titanium industry. For up-to-date information on business aspects of titanium, trade groups such as those listed in Appendix E can be contacted. However, some projections about the technical aspects of titanium use can be made:

- Titanium alloy compositions available and used in the near future will remain substantially the same as those available at the end of the twentieth century, although the relative mix of alloys may change. Aerospace product volume is declining; fewer funds are available for research. A result is that new titanium alloy composition development will diminish. Furthermore, nonaerospace applications are consuming more titanium than in the early years of titanium development. Most of these applications use existing alloys that are available with limited added development costs.
- Greater emphasis will continue to be placed on the use of cast alloys.
- Textured alloys may be accepted for selected applications. (While these are technically feasible, there still is no real driving factor behind the concept.)
- Superplastic forming in conjunction with bonding should increase in favor, although it may remain largely a process for the aerospace industry.
- Advanced P/M processed materials will continue to be worked, but extensive cost-effective applications are unlikely in the near future. Much development work will be needed before P/M techniques can effectively be applied to an application. A good property base does not yet exist.
- Rapid solidification rate (RSR) processing is comparable to P/M in application and is not likely to be useful for most commercial service.
- Aluminides will continue to be developed and tested for applications requiring higher-temperature capability, but economic application for industrial and commercial use is going to be limited for many years.

A Few Facts about Titanium and Its Production

Titanium is the ninth most-abundant element on the planet and the fourth most-abundant structural metal. Mineral sources of titanium are rutile, ilmenite, and leucoxene, an alteration product of ilmenite.

Principal world producers of ilmenite and titanium slag made from ilmenite are Australia, Canada, Norway, the Republic of South Africa, the United States, and Russia. Main producers of rutile are Australia, Sierra Leone, and the Republic of South Africa. Titanium sponge is produced mainly by Russia, Kazakhstan, the United States, Japan, the United Kingdom, and China. Titanium sponge and ingot are available worldwide.

The titanium business was in a state of flux during the 1990s. Consolidations and closures modified not only the business names but also the delivery of titanium services in the world. Since titanium operations start with the availability of sponge and then ingot for remelt, casting, or for subsequent working, it is desirable that some players in the titanium market be identified. The primary producers of titanium sponge and ingot in the United States at the end of the twentieth century were Timet, RMI, and Allegheny-Teledyne-Oremet.

In view of the fluidity of business operations, no other listing of titanium-related organizations is practical. When information is required, the appropriate trade organizations should be contacted as a start in locating titanium producers, fabricators, and other information for any titanium or titanium alloy application (Appendix E provides a listing of such organizations).

Appendix G: Machining Data

Selected References

The following listing provides references that contain tool life charts. These items may prove very helpful when making selections for milling titanium.

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