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Foreword

This two-volume handbook is a reference for engineering designers (materials engineers, metallurgists, etc.) involved in the complex and continuous process of materials selection.

Many types of materials are used for construction of commercial and military equipment. The primary materials used are metallics (for example, steel, aluminum, titanium, and nickel), nonmetallics (such as plastics and ceramics), and composites. Each of these classes of materials has a wide range of properties, presenting the designer with the formidable challenge of first choosing the proper class of material for a specific structure, and then determining the most appropriate material within the class selected. In making these decisions, the designer must review mechanical properties, corrosion resistance properties, and economic data for each material under consideration for completion of each structural engineering project.

Because the materials selection process depends to a large degree on mechanical and corrosion resistance properties, these handbooks emphasize the presentation of property data. Pertinent information on materials properties will assist the designer in selecting the most appropriate material for a specific application.

Michael L. Bauccio
Editor

About the Editor

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corrosion by galvanic coupling. Ti-6Al-4V (6-4) and Ti-6Al-2Sn-4Zr-2Mo (6-2-4-2) can be used in design applications where these alloys must be in direct contact with graphite epoxy composite material (GECM) (Ref. 17). The resistance of Ti-6-4 to electrochemical corrosion when coupled to GECM has been confirmed in other investigations (Ref. 84, 85). In these tests, Ti-6-4 was used for fasteners, which were connected to GECM and exposed to humidity and salt spray environments. A rivet that has been developed for composite material fastening consists of a Ti-6-4 shank and a Ti-Nb tail section. A Ti-Nb rivet has been used on the control surfaces of the F-18 and on the AV8B vertical short takeoff and landing aircraft (Ref. 15).

When titanium alloys are exposed to chemical environments containing chlorides or methyl alcohol, these materials may fail by SCC. The SCC failure will produce cracking at stress levels that are significantly lower than the specific titanium alloy tensile strength (Ref. 86).

Certain titanium alloys have been observed to crack under stress at about 370 °C (700 °F). Several types of chloride salts can induce failure, and this type of degradation has been referred to as hot salt stress-corrosion cracking (HSSCC). Alpha-phase titanium alloys that are most susceptible to HSSCC include Ti-5Al-2.5Sn, Ti-7Al-12Zr, and Ti-5Al-5Sn-5Zr. The most HSSCC-resistant titanium alloys include Ti-4Al-3Mo-1V, Ti-2.5Al-11Sn-5Zr-1Mo-0.2Si, and the experimental alloy Ti-2Al-4Mo-4Zr (Ref. 87).

Compared with other hcp metals, pure titanium is highly ductile. At room temperature, it can be cold rolled without significant cracking to greater than 90% reduction in thickness (Ref. 80). Aluminum is the most important substitutional additive in binary α -stabilized titanium alloys, because it adds to the ductility and light weight of titanium.

Advanced titanium materials have been fabricated using superplastic forming/diffusion bonding (SPF/DB) and hot isostatic pressing (HIP) (Ref. 88). Superplastic forming involves the extensive deformation of metals within a specific temperature range. The superplastic temperature range of Ti-6-4, for example, is 900 to 980 °C (1650 to 1700 °F) (Ref. 89). When Ti-6-4 and other medium-strength titanium alloys undergo SPF/DB, they elongate up to 1000%. They also diffusion-bond in the same temperature range, which is below the α - β transformation temperature (Ref. 90). SPF/DB has been utilized in the manufacture of parts for the B-1 bomber, including the large lower engine access door (Ref. 91). SPF/DB technology also has been applied in the fabrication of a cylindrical missile section for the U.S. Navy. Ti-6-4 is the material that has been used in the manufacture of these missile components. With the SPF/DB method, the cylindrical missile parts have been bonded and formed in a

single set of operations. Generally, the use of SPF/DB in the manufacture of military hardware has enhanced the desirability of using titanium alloys, because the end products are lower in cost (Ref. 88).

HIP can be used for titanium, as well as for other metals and ceramics (Ref. 92). In this process, materials are pressurized with an inert gas, usually argon, at high temperatures (up to 2000 °C, or 3630 °F). Pressures of up to 204 MPa (30 ksi) are applied isostatically to the parts. The HIP process produces castings with dense, homogeneous microstructures, which generally increase fatigue life.

For high performance and structurally efficient aerospace and automotive components, the most widely used titanium alloys belong to the two-phase (α - β) microstructural classification. These titanium alloys are attractive because of their high strength and light weight. A major application of titanium is in military aircraft gas turbine engines (Ref. 93). Future use of titanium alloys in engines may increase through the implementation of rapid solidification technology (RST) (Ref. 94).

Ti-6-6-2 is a forgeable alloy with greater hardenability than Ti-6-4. For example, uniform hardening can be accomplished in 100-mm (4 in.) thick sections with Ti-6-6-2, compared with only 25 mm (1 in.) thick sections when Ti-6-4 is used.

Ti-8Mo-8V-2Fe-3Al (Ti-8-8-2-3) is another candidate material for use in heavy sections and forgings. Based on comparison of some of the mechanical and physical characteristics of these materials, Ti-8-8-2-3 is similar to Ti-6-6-2. Ti-8-8-2-3, for example, can be deep-hardened, and it is able to retain its high strength to 340 to 370 °C (650 to 700 °F) (Ref. 31).

Ti-6Al-2Sn-4Zr-2Mo (Ti-6-2-4-2) may be used in applications requiring high strength and toughness at temperatures up to 500 to 540 °C (940 to 1000 °F). This alloy may be used for forgings and flat-rolled products in gas turbine engine and airframe applications.

Ti-6Al-2Sn-4Zr-6Mo (Ti-6-2-4-6) is another high-strength titanium alloy that can be used in gas turbine engines, particularly in the disk and fan blade components of compressors. Ti-6-2-4-6 should be considered for long-duration load-carrying applications at temperatures up to 400 °C (750 °F), and for short-duration load-carrying structures at temperatures to 540 °C (1000 °F).

Refractory Metals

Refractory metals are elements that have melting points greater than 2204 °C (4000 °F). For example, tungsten melts at 3410 °C (6170 °F). In addition to tungsten, the following are also refractory metals: niobium (Nb), molybdenum (Mo), hafnium (Hf), rhenium (Re), and tantalum (Ta). All of these metals have substantial potential for use in military equipment, especially aerospace and electronics components.

In addition to their very high melting points, the desirable characteristics of refractory metals include:

- Resistance to electrochemical corrosion (applies especially to tantalum, whose corrosion resistance is comparable to that of glass) (Ref. 95)
- Excellent high-temperature strength
- High resistance to thermal shock (applies to tungsten)
- Excellent resistance to wear and abrasion
- Good electrical and heat-conducting properties

The most easily fabricated refractory metals are niobium, tantalum, and their alloys. Fabricability is often used as a deciding factor in the selection of a specific refractory metal (Ref. 96).

Refractory metals are often used as alloying elements (Ref. 97). For example, the currently used wear-resistant alloys may include either tungsten or molybdenum combined with cobalt and chromium. Also, large amounts of tungsten have been used in cobalt-base alloys requiring high-temperature strength and resistance to high radial stresses (Ref. 98). Molybdenum has been used as an alloying element in a stress-corrosion-resistant material, multiphase MP35N, which has been used for aircraft fasteners.

Development of the tantalum-base refractory alloys T-111 and T-222 was the result of extensive government-sponsored work to improve the creep resistance of tantalum alloys. T-222 is the standard material to which other tantalum alloys are compared. T-222 has attractive mechanical properties at pyrogenic and cryogenic temperatures. This alloy is also easily welded, has a ductile-to-brittle transition temperature well below -18 °C (0 °F), possesses good fabricability, and is easy to produce (Ref. 99). T-222 also has substantially better creep rupture properties in comparison to other refractory materials.

Refractory metal alloys satisfactorily retain their mechanical strength at elevated temperatures. Minor additions of zirconium and hafnium to Ta-W-Mo alloys have produced significant strengthening up to 1930 °C (3500 °F)

(Ref. 99, 100). This strengthening effect due to alloying of refractory metals has been reported at 1480 °C (2700 °F).

Some of the unsatisfactory characteristics of refractory metals include their high cost and poor fabricability (except for niobium and tantalum, which can be formed, machined, and joined by conventional methods) (Ref. 96). Refractory metals are susceptible to accelerated atmospheric oxidation, which occurs at about 200 °C (400 °F) for tungsten, 400 °C (750 °F) for molybdenum, and 430 °C (800 °F) for tantalum and niobium. Coatings which consist of more than one element, referred to as composite coating systems, have been tested for high-temperature oxidation protection of refractory metals. A composite coating consisting of Hf-20Ta was observed to be resistant to erosion, thermal cycling, and oxidizing environments from about 1760 to 2200 °C (3200 to 4000 °F). However, oxidation resistance from 1090 to 1650 °C (2000 to 3000 °F) needs further improvement. Additional corrosion protection is required to prevent degradation of the substrate metal. Examples of possible mechanisms in substrate metal degradation include an increase in the ductile-to-brittle transition temperature and poor oxidation in certain localized areas, particularly edges and corners (Ref. 96).

For the application of niobium alloys in high-temperature conditions, the use of various types of silicide or aluminide coatings is necessary (Ref. 96, 100). Elevated-temperature applications for niobium alloys B-66 and Cb-752 include gas turbine blades and vanes, shrouds, and rocket engine nozzles. B-66 and silicide-coated Cb-752 also are used in the lifting and guidance structures of glide re-entry vehicles (Ref. 31).

Refractory metals have been used in the alloying of heat-resistant nickel-base superalloys. Niobium, molybdenum, tungsten, and tantalum are often added to nickel-base superalloys for solid solution strengthening of the superalloy matrix (Ref. 101, 102). In nickel-cobalt-chromium (Ni-Co-Cr) base alloys that are used for single crystal gas turbine blades, 12% tantalum has been added. Tantalum is also widely used in the manufacture of electrolytic capacitors (Ref. 103).

For military electronic equipment applications, tungsten has substantial potential. An example is the use of tungsten in very large scale integrated circuits. Tungsten serves as a diffusion barrier (interface) between aluminum interconnecting lines and silicon chips (Ref. 104). This tungsten interface prevents the shorting of metal-oxide semiconductor circuits.

Superalloys

Superalloys are metallic materials that contain chromium and other elements to enhance resistance to oxidation and hot corrosion, and to maintain strength at high temperatures. Oxidation is defined as the reaction of an alloy with oxygen in the presence of combustion products from an uncontaminated fuel. Hot corrosion is aggressive corrosive degradation produced by oxidation and by reactions with sulfur and other contaminants (Ref. 105).

Superalloys are classified as follows:

- **Iron-base:** Iron-base superalloys are hardened by carbides, intermetallic precipitates, and/or solid solution strengthening elements such as molybdenum and tungsten. Typical alloys in this class include A-286, MULTIMET alloys[†] and Haynes 556.
- **Cobalt-base:** These materials contain cobalt as the major constituent with some solid solution strengthening secondary phase carbides or intermetallic compounds. Some of the cobalt-base superalloys that can be used in the 650 to 1150 °C (1200 to 2100 °F) temperature range are Haynes 25, Haynes 188, UMC0-50, and S-816.
- **Nickel-base:** These heat-resistant alloys contain approximately 30 to 75% Ni, with up to 30% Cr. Small amounts of aluminum, titanium, niobium, molybdenum, and tungsten are added to nickel-base superalloys to increase strength, corrosion resistance, or both. In order to conserve cobalt, Ni-Cr alloys have been developed. These Ni-Cr materials have the same abrasion resistance as Co-Cr alloys, but the galling and cavitation erosion resistance of Ni-Cr alloys is less than that of the Co-Cr alloys (Ref. 106).

For superalloys used mainly in high-temperature gas turbine applications, the most significant physical properties are density, expansion coefficient, and thermal conductivity.

The development of iron-base and iron-nickel-base superalloys has been much slower than that of cobalt-base and nickel-base superalloys. Nickel-base superalloys are the largest class of these materials, but cobalt-base superalloys have received considerable attention for high-temperature applications because the melting point of cobalt is 40 °C (100 °F) higher than that of nickel (Ref. 31). Most of the cobalt-base alloys that are produced, therefore, are used in high-temperature gas turbine parts (Ref. 97).

Advanced cobalt-base and nickel-base superalloys, including the mechanically alloyed (MA), oxide dispersion-strengthened (ODS) MA 6000, may be used up to 1090 °C (2000 °F) (Ref. 31, 107). The nickel-base ODS alloys, such as MA 6000, derive their strength from uniformly dispersed and stable oxides. In mechanical alloying ODS alloys are

produced by a constant fracturing and rewelding of a mixture of metal powders and oxide particles.

Nickel-base superalloys also have been strengthened by precipitation of a gamma-prime (γ') phase or a gamma double prime (γ'') phase (Ref. 102, 108). Two examples of the γ phase are Ni_3Al and Ni_3Ti . The addition of cobalt to nickel-base superalloys may produce $(\text{Ni},\text{Co})_3(\text{Al}, \text{Ti})$, in which cobalt substitutes for some of the nickel (Ref. 50).

The γ' phase hardens the nickel-base superalloy matrix as temperatures increase to approximately 800 °C (1470 °F). Inconel X-750 is a precipitation-hardened nickel-base superalloy. At 540 °C (1000 °F), its yield strength is about three times that of Inconel 600, which is not strengthened by intermetallic precipitation.

The creep-rupture strength of superalloys is one of the most significant properties to consider during the material selection process. The high-temperature (760 to 1200 °C, or 1400 to 2200 °F) creep-rupture characteristics of nickel-base superalloys are superior to those of either the cobalt-base or nickel-iron-base superalloys. Cast nickel-base superalloys, such as MAR-M246, maintain the highest stress-rupture strengths at elevated temperatures. Multistage heat treatments increase both the strength and ductility of cast nickel-base superalloys used in aircraft engines (Ref. 48).

Both nickel- and cobalt-base materials can be used for hardfacing applications, where resistance to abrasion and wear is necessary (Ref. 97, 106, 109, 110). These hardfacing alloys are used in equipment in which nonlubricated components move relative to each other. Nickel-base hardfacing alloys generally are used in applications where both corrosion and abrasion resistance are required. Cobalt-base hardfacing alloys, which are used in diesel engine components, are used for parts that must endure high stress metal-to-metal wear. These cobalt-base alloys are used particularly in nonlubricated parts.

The fatigue crack propagation (FCP) behavior of nickel-base superalloys is another important characteristic to consider in the selection process for these materials. The stress intensity factor (K) can be correlated to the FCP behavior of nickel-base superalloys (Ref. 111). For FCP rates exceeding about 2.5×10^{-5} mm/cycle (10^{-6} in./cycle), the data are very well represented by the Paris equation:

$$\frac{da}{dN} = C(K)^n$$

where da/dN is the measured crack growth rate, and C and n are material constants at certain temperatures, frequencies, and load ratios. For Waspaloy, the FCP rates (with respect to K) were best with material that had coarse grains and fine γ' particles (Ref. 111).