

Microstructure and Properties of Materials

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PREFACE

This is the second volume of an advanced text book set on the microstructure and properties of materials. The first volume is on aluminum alloys, Nickel-base superalloys, metal matrix composites, polymer matrix composites, ceramics matrix composites, inorganic glasses, superconducting materials and magnetic materials. This volume covers titanium alloys, titanium aluminides, Iron aluminides, iron and steels, iron-base bulk amorphous alloys and nanocrystalline materials.

More specifically Chapter 1 on titanium alloys covers the production, thermomechanical processing, microstructure, mechanical properties and applications. Chapter 2 on titanium aluminides discusses phase stability, bulk and defect properties, deformation mechanisms of single phase materials and polysynthetically twinned crystals and interfacial structures and energies between phases of different compositions. Chapter 3 on Iron Aluminides reviews the physical and mechanical metallurgy of Fe_3Al and FeAl , the two important structural intermetallics. Chapter 4 on iron and steels presents methodology, microstructure at various levels, strength, ductility and strengthening, toughness and toughening, environmental cracking and design against fracture for many different kinds of steels.

Chapter 5 on bulk amorphous alloys shows the critical cooling rate and the effect of composition on glass formation and the accompanying mechanical and magnetic properties of the glasses. Chapter 6 on nanocrystalline materials describes the preparation from vapor, liquid, and solid states, microstructure including grain boundaries and their junctions, stability with respect to grain growth, particulate consolidation while maintaining the nanoscale microstructure, physical, chemical, mechanical, electric, magnetic and optical properties and applications in cutting tools, superplasticity, coatings, transformers, magnetic recordings, catalysis and hydrogen storage.

Material problems are important for almost all industries. New materials are needed daily. But the principles and the relationships between properties and microstructure remain similar. The more we know about these relations the easier will be to find new materials with desired properties. If you would like to see certain material included in the third volume, please email me at li@me.rochester.edu.

James C. M. Li
Rochester, NY
October, 1999

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Chapter 1

MICROSTRUCTURE AND MECHANICAL PROPERTIES OF TITANIUM ALLOYS

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1. Introduction

Titanium was first identified as a new and unknown metallic element by Gregor in England (1791), and was named Titanium several years later (1795) by Klaproth in Germany after the Titans of the Greek mythology. The production of high-purity titanium proved to be difficult, because of the strong tendency of this metal to react with oxygen and nitrogen. Therefore, it was not until the middle of the 20th century (1938-1940) that a commercially attractive process was developed by W.J. Kroll in Luxemburg. This process involves the reduction of titanium tetrachloride with magnesium in an inert-gas atmosphere. The resulting titanium is called "titanium sponge" because of the porous, spongy appearance. The commercial interest in titanium and its alloys was prompted by the relatively low density of this metal (between those of aluminum and iron) in combination with a high yield strength (especially in the 200-450°C range), and its excellent corrosion resistance. Therefore, titanium and its alloys are used primarily in two areas of applications: corrosion resistant areas, such as the chemical industry, and in areas where weight-savings and high strength are predominant, such as in aircraft and aerospace applications. This introductory section is not intended to give an in-depth overview on the basic properties of titanium, but only to briefly summarize some of the findings which are important with regard to the main subject of this chapter on microstructure/property relationships of titanium alloys.

The existing literature on titanium alloys is well documented in the Proceedings of the International Conferences on Titanium, which were held with one exception every four years: 1968 in London [1], 1972 in Boston [2], 1976 in Moscow [3], 1980 in Kyoto [4], 1984 in Munich [5], 1988 in Cannes [6], 1992 in San Diego [7] and 1995 in Birmingham [8], the next conference being 1999 in St. Petersburg.

1.1 Crystal Structure

Titanium undergoes an allotropic phase transformation at 882.5 °C, changing from a closed-packed hexagonal crystal structure (α phase) below, to a body-centered cubic crystal structure (β phase) above this temperature. The exact transformation temperature is strongly influenced by interstitial and substitutional elements, therefore depending on the purity of the metal. The hcp unit cell of the low temperature α phase is shown in

Figure 1a, together with the three most densely packed lattice planes and the lattice parameters at room temperature. The resulting ratio $c/a = 1.587$ for pure α -Ti is smaller than the ideal ratio for a hexagonal closed packed crystal structure with $c/a = 1.633$. The unit cell of the bcc β phase is illustrated in Figure 1b, exhibiting one variant of the most densely packed $\{110\}$ lattice planes, and the lattice parameter of pure β -Ti at 900 °C.

The intrinsic anisotropic behavior of the hexagonal crystal structure of the α phase has important consequences for the elastic and plastic deformation behavior of titanium and its alloys, besides on numerous other physical properties. The variation of Young's modulus E of pure α -Ti single crystals at room temperature as a function of the angle γ between the c -axis of the unit cell and the stress axis is shown in Figure 2 [9], resulting in modulus variations between 145 GPa (stress axis $\parallel$ c -axis) and 100 GPa (stress axis $\perp$ c -axis). Similar strong variations are also observed for single crystal shear modulus values G of 46 GPa and 34 GPa for shear stresses applied in (0002) and $\{10\bar{1}0\}$ planes, respectively, with the stress axis being parallel to $\langle 11\bar{2}0 \rangle$. Although such differences are smaller in polycrystalline α -Ti and its alloys, there can be still pronounced variations for highly textured material (see Section 2).

The elastic moduli are decreasing almost linearly with increasing test temperature up to the transformation temperature. For polycrystalline α -Ti without texture the Young's modulus drops from about 110 GPa at RT to about 58 GPa just below the transus, while the shear modulus decreases from about 42 to 20 GPa in the same temperature interval [e.g. 10].

Since the β phase of pure Ti cannot be retained at RT, Young's modulus values are shown here for binary Ti-V solid solution alloys in Figure 3. The moduli of β -Ti increase with increasing solute content and their values are much lower as compared to those in α -Ti. In general, commercial β -Ti alloys exhibit E -moduli at RT in the range of 70 to 90 GPa, while α and $\alpha+\beta$ Ti-alloys show values which are always above 100 GPa [11].

1.2 Deformation Modes

The observed ductile behavior of α -Ti, also at low testing temperatures, results from the combined contribution of slip and twinning modes.

1.2.1 Slip Modes

The various slip systems observed in α -Ti are summarized in Table 1 and corresponding slip planes and slip directions in the hcp unit cell are shown in Figure 4. The three slip systems in Table 1, which all have the same $\bar{a}$ type Burgers vector, together possess nominally 8 independent slip systems. However, this number reduces to only 4 systems since the changes of shape that can be produced by the combined slip systems 1+2 are exactly the same as those of the slip system 3. In no case is an extension parallel to the c -axis possible. Therefore, in order to satisfy the von Mises criterion, which requires at least five independent slip systems for a homogeneous plastic deformation of

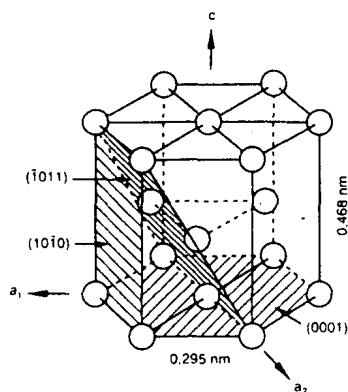
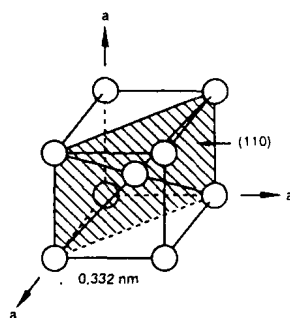
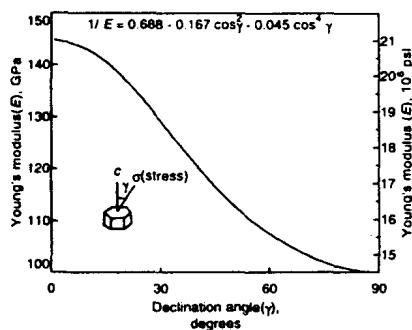
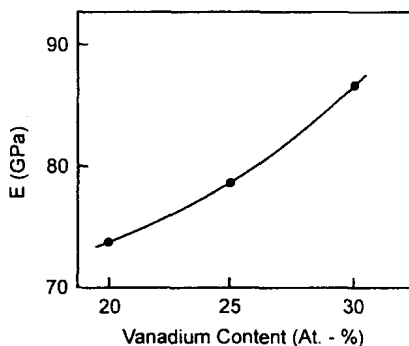

a) hcp α phase

b) bcc β phase

Fig. 1: Unit cells of α and β phases.

Fig. 2: Variation of Young's modulus (E) in α -Ti single crystals with declination angle (γ) [9].

Fig. 3: Young's modulus (E) as a function of Vanadium content in β Ti-V solid solution alloys.