

Chapter 2

Metallurgy and Microstructure

2.1 The General Metallurgy of Titanium Alloys

Unalloyed titanium has two allotropic forms. The low temperature form, α , exists as an hexagonal-close-packed (hcp) crystal structure up to 882°C, above which it transforms to β , which has a body-centred-cubic (bcc) crystal structure.

The alloying behaviour of elements with titanium is defined by their effects on α and β . Element additions that increase or maintain the temperature range of stability of the α phase are called α -stabilizers. The most important of these are aluminium, tin and zirconium. Element additions that stabilize the β phase are called β -stabilizers. These include molybdenum, vanadium and iron.

There are also important impurity elements, namely oxygen, hydrogen, nitrogen and carbon. Oxygen and hydrogen are the two most important impurities: oxygen is an α -stabilizer and hydrogen is a β -stabilizer. These four elements are also referred to as interstitial elements. This is because their atomic sizes are much less than those of the metallic alloying elements and they fit in the spaces (interstices) between the crystallographic positions of the metal atoms in the α and β phases.

Titanium alloys can be classified in four categories:

- | | |
|-------------------------------|---|
| (1) α alloys | Examples are commercially pure grades of Ti, containing well-defined amounts of oxygen, and Ti-2.5Cu and Ti-5Al-2.5Sn. |
| (2) Near- α alloys | These contain only a small amount of β phase. They are heat-treatable and stronger than α alloys. Early examples are Ti-6Al-2Sn-4Zr-2Mo and Ti-8Al-1Mo-1V. More complex alloys have been developed for improved creep resistance. These include TiAlZrMoSiFe and TiAlZrSnNb(Mo,Si) alloys. |
| (3) α - β alloys | These contain limited amounts of β -stabilizers, the majority of which cannot strengthen the α phase. Hence α -stabilizers are also added. The mechanical properties depend on the relative |

(4) β alloys

amounts and distribution of the α and β phases. These variables are controlled by processing and heat treatment. Examples are Ti-6Al-4V and Ti-6Al-2Sn-4Zr-6Mo.

These have sufficiently high β -stabilizer contents that commercially useful microstructures are predominantly β phase. They have been developed mainly because of excellent formability (e.g. cold-rolling) and very good response to heat treatment. Examples are Ti-15Mo-3Nb-3Al-0.2Si and Ti-10V-2Fe-3Al.

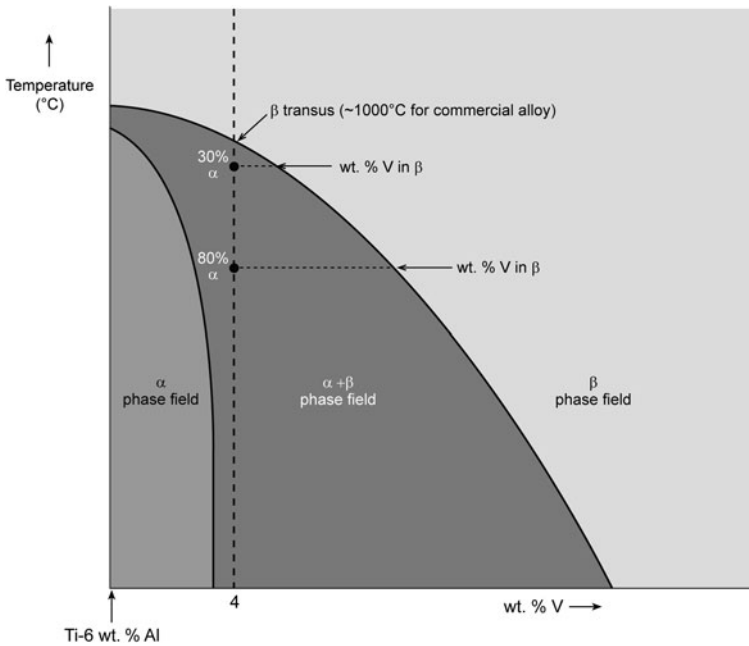


Fig. 2.1 Pseudo-binary equilibrium phase diagram (schematic) for Ti-6Al-4V. The relative amounts of α at the two indicated temperatures are derived from the metallurgical phase diagram *lever rule*

2.2 Conventional Thermomechanical Processing of Alloys Like Ti-6Al-4V

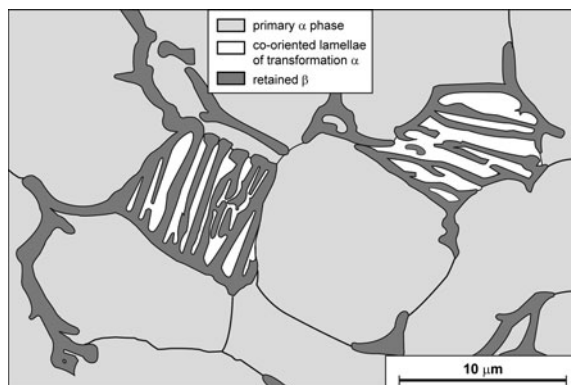
The most important parameter in thermomechanical processing and heat treatment of α - β titanium alloys is the β transus temperature. Figure 2.1 shows a schematic phase diagram for Ti-6Al-4V. Above the β transus the alloy is 100% β and is relatively easily worked. But β working has, or can have, adverse effects on some

mechanical properties, and so can β heat treatment, see Sect. 2.3. Consequently, even though initial working may be in the β phase field, final working is conventionally in the $(\alpha + \beta)$ phase field and any subsequent conventional heat treatments are also in the $(\alpha + \beta)$ phase field.

However, this is not the whole story, since the mechanical properties of α - β alloys depend on the relative amounts and distribution of the α and β phases. These variables depend strongly on the thermomechanical processing and heat treatment temperatures in the $(\alpha + \beta)$ phase field. For example, Fig. 2.1 indicates the percentage of primary α in Ti-6Al-4V at two temperatures. At the higher temperature there is less *primary* α and more β , which, however, contains less vanadium. Since vanadium is a β -stabilizer, this means that the higher temperature β more readily transforms to α during cooling after processing, and also during any subsequent heat treatment at relatively low temperatures, e.g. annealing at 700–750°C.

When β transforms to α , the morphology of the *transformation* α is very different to that of *primary* α . Figure 2.2 illustrates this schematically: prior β grains have transformed to co-oriented α lamellae (*transformation* α) separated by ribs of retained β . The crystallographic significance of this transformation is discussed in Sect. 2.4, but here it is worth noting that manufacturers impose property-driven requirements on the relative amounts of primary α and transformed β in conventionally processed Ti-6Al-4V. An excellent overview is provided by Wedden and Liard (1973).

Fig. 2.2 Illustration of an α - β titanium alloy duplex microstructure, showing more or less equiaxed grains of primary α and transformed β . The transformation of β results in co-oriented α lamellae (*transformation* α) separated by “ribs” of retained β



2.3 β Processing and/or β Heat-treatment

The use of β processing and/or β heat-treatment for α - β titanium alloys is generally regarded as inadvisable. Forging above the β transus is more difficult to control and can lead to coarse-grained microstructures detrimental to alloy strength, ductility and fatigue properties, as can β heat-treatment (Coyne 1970;

Green and Minton 1970; Donachie 1982, 2000; Terlinde et al. 2003; Wagner 1997; Evans 1999).

However, it has long been recognized that β annealing of Ti-6Al-4V, although it significantly reduces the strength, is beneficial to the DT&D-related properties of long/large fatigue crack growth, fracture toughness and stress corrosion cracking resistance (Paton et al. 1976). This recognition has recently led to the introduction of β annealed Ti-6Al-4V thick plate for large primary structures in advanced aircraft, as mentioned in Chap. 1.

It is important to note here that β annealing has become an accepted heat-treatment for optimizing the creep resistance of some near- α alloys used in aeroengine (gas turbine) compressors (Peters et al. 2003). The ambient temperature fatigue crack growth properties of these alloys provide data to be discussed and compared with similar data for β annealed Ti-6Al-4V in Chaps. 5 and 6.

2.4 Crystallography of the $\beta \rightarrow \alpha$ Phase Transition

The transformation of metastable β phase to stable α phase obeys—approximately—the following crystallographic relationships for each transforming β grain (Newkirk and Geisler 1953; Williams et al. 1954):

- (1) One $\{110\}_\beta$ plane parallel to $\{0002\}_\alpha$.
- (2) One $\{112\}_\beta$ plane parallel to one $\{10\bar{1}0\}_\alpha$.
- (3) One $\{112\}_\beta$ plane at 9° to one $\{10\bar{1}0\}_\alpha$.
- (4) $\langle 111 \rangle_\beta$ parallel to $\langle 11\bar{2}0 \rangle_\alpha$.

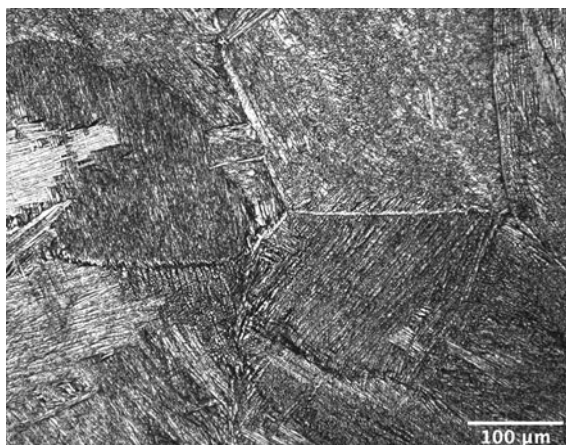
These relationships are significant because they show that slip compatibility, due to crystallographic parallelism, is possible between transformation α and retained β . In practice this has the important consequence that when slip initiates in co-oriented α lamellae the retained β ribs between the lamellae are not effective barriers to slip extension.

2.5 Microstructure of β Annealed Ti-6Al-4V ELI Thick Plate

Figure 2.3 gives an example of the microstructure near the mid-thickness of a thick plate (125 mm) of β annealed Ti-6Al-4V ELI acquired for the DSTO–NLR joint programme. The β annealing heat treatment resulted in a fully lamellar microstructure consisting of large colonies of co-oriented α lamellae within the prior β grains, which are delineated by grain boundary α .

Figure 2.3 also shows that the aligned α platelets are separated by thin ribs of retained β . As discussed in Sect. 2.4, these ribs are likely to be ineffective barriers

Fig. 2.3 Example microstructure (Kroll's etch) of the β annealed Ti-6Al-4V ELI thick plate acquired for the DSTO–NLR joint programme. This example shows large colonies of co-oriented α lamellae within prior β grains, with grain boundary α delineating the prior β grains. The prior β grain sizes in the plate were found to range from about 0.2 to 2 mm, with a mean of 1.2 mm



to slip. However, the colonies themselves have differing crystallographic orientations and would therefore be expected, like the prior β grain boundaries, to act as barriers to slip. In fact, the boundaries between the colonies and the prior β grains are not always effective slip barriers, as will be shown in [Sect. 3.2](#).

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