The high strength β titanium alloys Ti-17 and Ti-6246 are used in the compressor part of aero-engines replacing the Ti-6Al-4V alloy because of their higher basic strength. A good example is the large Ti-17 fan disk shown in Fig. 3.24 which is used in the GE-90 aero-engine. The fan disk shown in that figure has an outside diameter of about 800 mm and is manufactured from three separate forgings which are welded together using solid state inertia welding (see Sect. 3.6.2). The three pieces are β forged and conventionally heat treated, i.e. they received the two-stage heat treatment shown in Fig. 7.7 (steps IVa and IVb). Since the β grains in the fan disk forgings will be pancake shaped typical for β processed material (see Sect. 7.1.2) with the thin dimension parallel to the axial direction of the disk. The major applied stresses acting on the fan disk will be parallel to the pancake plane of the β grains, only the properties described in Sect. 7.2.1 as properties in L test direction of β processed material (see also Table 7.7) will be important.

As described already in Sect. 5.3, the LCF strength, i.e. a combination of fatigue crack nucleation resistance and microcrack propagation resistance, is the important design criteria for compressor disks. Both of these properties are good in L testing direction (Table 7.7) considering the anisotropy of the pancake shaped β grains. It should be pointed out, however, that those properties would be even better for the bi-modal microstructure and that the major drawback of the bi-modal microstructure, the low fracture toughness (see Fig. 7.27), is not important for compressor disks, because the fracture toughness has an insignificant effect on life time and no effect on inspection intervals, see discussion in Sect. 5.3. As also pointed out already in Sect. 5.3, for fatigue life calculations of disks based on fatigue crack propagation data it is important to use the microcrack propagation data because macrocrack propagation data would result in overestimation of cycles to failure (see Fig. 7.25).

As described at the end of Sect. 7.2.2, high strength β titanium alloys are also used in the hotter part of aero-engine compressors up to about 400°C. An example can be seen in Fig. 3.78 which is a two-stage HP compressor rotor made out of the high strength β titanium alloy Ti-17. The production route for this HP compressor rotor is the same as described above for the fan disk, i.e. the individual disks or stages are β processed, heat treated, inertia welded together, and finally machined. The high yield stress after aging of this high strength β alloy Ti-17 results in the required adequate creep strength in addition to the good LCF strength. LCF strength was discussed above for the fan disk. Creep strength is an additional requirement for elevated temperature application.

Another application using relatively large forgings of the high strength β alloy Ti-10-2-3 is the Super Lynx helicopter rotor head shown in Fig. 7.42. The three different forgings made out of Ti-10-2-3 are indicated in that figure. In this case, the HCF strength is the most important design criteria. This is a complete different requirement as compared to the large Ti-10-2-3 forging discussed earlier (high fracture toughness requirement for the truck beam forging in Fig. 7.37). For forging the helicopter rotor head parts, the final α+β forging apparently used (although not discussed in the open literature) leads to some kind of bi-modal microstructure (see Figs. 7.13 and 7.14) which is the correct microstructure to obtain a high HCF
strength and which is even higher than for $\beta$ processed material tested in L direction, see Sect. 7.2.1.2. On the example of the disk forging for the rotor head arms, the influence of various microstructural parameters on mechanical properties was measured and discussed in detail and the results can be found in [7.23]. Most of these results were the basis for an overview paper [7.24] on microstructure/property relationship in $\beta$ titanium alloys containing also a summary table similar to Table 7.7.

Another area, for which heavily stabilized $\beta$ titanium alloys are used, is the so-called downhole service area (oil and gas drilling and production, geothermal wells, etc.). The primary advantages of these $\beta$ alloys over the Ti-6Al-4V alloy for this kind of application are the higher yield stress and the lower modulus of elasticity combined with equal or better corrosion resistance in aggressive environments. Particularly Beta C is used for these applications [7.25] with the usual $\beta$ annealed and aged microstructure. It should be mentioned again, that for this $\beta$ annealed microstructure the mechanical properties have to be adjusted either by the size of the equiaxed grains (Sect. 7.2.3) or by the aging treatment (Sect. 7.2.2).

Other application areas of $\beta$ titanium alloys are in the biomedical field, in automobiles, and in the area of sporting goods. These applications will be covered in the relevant sections of Chap. 10.

Fig. 7.42. Helicopter rotor using forgings of Ti-10-2-3 (courtesy G. Terlinde, Otto Fuchs Metallwerke)

7.4 Recent Developments since the First Edition

7.4.1 Effect of Yield Stress Level on Properties of Ti-6246

A key to understanding the properties of high strength $\beta$ titanium alloys is the effect of strength difference between the age-hardened matrix and the soft zone along the continuous $\alpha$ layer at $\beta$ grain boundaries. Studies on Ti-6246 with varying yield stress (matrix strength) from about 1000 MPa to approximately 1700
MPa have been performed. The yield stress variation was achieved using different heat treatments [7.26]. In addition, this variation was done for three different types of microstructural conditions (β annealed, β processed, and bi-modal) described in Sects. 7.1.1, 7.1.2, and 7.1.4. Examples are shown in Fig. 7.43.

Fig 7.43. Size and shape of β grains for three microstructural conditions in Ti-6246, LM: (a) β annealed (b) β processed (c) Bi-modal
The β annealed condition exhibited a recrystallized equiaxed grain structure with a β grain size of about 500 μm (Fig. 7.43a). In the β processed condition, the β grain structure was unrecrystallized and pancake shaped (Fig. 7.43b) with average dimensions of about 800 μm in L and T directions and 200 μm in ST direction (see also Fig. 7.24). The fracture related properties of this β processed condition are anisotropic as discussed in Sect. 7.2.1. In contrast to the other two microstructures, the properties of this β processed condition were evaluated only in the L direction (stress axis) because this can be taken as the relevant direction for compressor discs. The bi-modal microstructure was obtained by α+β processing and subsequent recrystallization in the (α+β) phase field (see Fig. 7.13). The resulting equiaxed β grain size was about 20 μm, see Fig. 7.43c.

In tensile tests crack nucleation will be influenced by the strength difference between the age-hardened matrix and the soft zones along the α layers at β grain boundaries and by the slip length within the soft zone, i.e. β grain size and grain shape. Figure 7.44 shows the tensile elongation as a function of yield stress for the three different microstructural conditions investigated. It can be seen that the tensile ductility is reduced to zero at a yield stress level of about 1300 MPa for both the β annealed and the β processed conditions. At the same strength level, the bi-modal microstructure exhibited a tensile elongation of about 10%.

Fig. 7.44. Tensile elongation as a function of yield stress, Ti-6246
Even at the highest yield stress (1680 MPa), the bi-modal microstructure exhibited measurable ductility (tensile elongation 0.5%) whereas in this high yield stress region the β annealed and β processed microstructures fractured before yielding on a macroscopic scale. On a microscopic scale these specimen showed a ductile dimple fracture mode with the crack path following the β grain boundaries, i.e. in the soft zone adjacent to the continuous α layer.

Fracture toughness as a function of yield stress for the three microstructural conditions is shown in Fig. 7.45. It can be seen that in the low yield stress region (≤ 1150 MPa) the fracture toughness is following the well-known trend. The β processed material exhibits the highest fracture toughness followed by the β annealed material and the lowest fracture toughness is measured for the fine grained bi-modal material. With increasing yield stress, the curves approach each other and in the high yield stress region (≥ 1350 MPa) the ranking seems to change. The bi-modal microstructure exhibits now slightly higher fracture toughness as compared to the β processed and β annealed structures. Examples of the fracture surfaces are shown in Fig. 7.46. This figure also compares the fracture surfaces for the low and the high yield stress conditions of the three different microstructures.

![Fracture Toughness vs Yield Stress](image-url)

Fig. 7.45. Fracture toughness as function of yield stress, Ti-6242
Fig. 7.46. Fracture surfaces of \( K_e \) specimens at low yield stress (left side) and at high yield stress (right side), Ti-6246, SEM: (a, b) \( \beta \) annealed (c, d) \( \beta \) processed (e, f) Bi-modal

Firstly, it can be seen that the fracture surface of the bi-modal condition is very smooth in contrast to the other two microstructures. Secondly, the fracture mode is qualitatively the same in the low and high yield stress regimes with the tendency that the percentage of crack propagation along \( \beta \) grain boundaries, i.e. within the soft zone adjacent to the continuous \( \alpha \) layer, is increasing slightly with increasing
yield stress level. This can be seen in Fig. 7.46 for the β annealed and β processed conditions. For the bi-modal condition, the same magnification was used in Fig. 7.46 for comparison purpose but the magnification is too low to provide much detail. Micrographs taken at higher magnification showed also the above described tendency.

The dependence of fracture toughness on yield stress shown in Fig. 7.45 for the three microstructural conditions can be qualitatively understood by considering two separate contributions to fracture toughness. One is the intrinsic contribution and the other is the crack front geometry contribution, as discussed in Sects. 5.2 and 7.2. These contributions are separated in the schematic drawing, Fig. 7.47. The intrinsic contribution to fracture toughness which describes the propensity for crack propagation within the soft zones is influenced by the strength difference between matrix and soft zones, i.e. yield stress level, and by the slip length (grain boundary length). This intrinsic contribution (Fig. 7.47) declines more rapidly with increasing yield stress for the β annealed and β processed microstructures as compared to the bi-modal microstructure. This is because the β annealed and β processed microstructure have a longer slip length (grain boundary length) as compared to the bi-modal microstructure. This is reflected in the two intrinsic contribution curves in Fig. 7.47.

The crack front geometry contribution to fracture toughness which is much bigger for the coarse grained β annealed and β processed structures than for the fine grained bi-modal structure does not depend to a large degree on the yield stress level as can be deduced from the fracture surfaces in Fig. 7.46. Therefore, this factor makes a contribution to fracture toughness that is essentially independent of
7.4 Recent Developments since the First Edition

yield stress. Therefore, the two geometry contribution curves in Fig. 7.47 have very little slope. The sum of these two contributions represents the fracture toughness. This accounts for the observed strength-toughness trends (Fig. 7.45). That is, the bi-modal structure has a lower fracture toughness in the low yield stress regime but a higher fracture toughness in the high yield stress regime as compared to the $\beta$ annealed and $\beta$ processed microstructures. This is because the two sum curves in Fig. 7.47 cross. The yield stress that corresponds to the crossover of the two sum curves in Fig. 7.47 depends on the slopes of the intrinsic contribution curves as well as on the height of the crack front geometry contribution curves. This means that the crossover yield stress will depend on the alloy type as well as on the details of the thermo-mechanical treatments used.

In addition to tensile and fracture toughness tests, S-N curves were measured for the three microstructural conditions. The $10^7$ cycles fatigue strength values obtained from the S-N curves are plotted in Fig. 7.48 as a function of yield stress. It can be seen from the results that the high cycle fatigue (HCF) strength was about the same for all microstructures with yield stress values up to 1200 MPa.

Fig. 7.48. HCF strength (RT, $R = -1$, 75 Hz) as a function of yield stress, Ti-6246
The scatter for the β processed condition is greater but the average values are represented by the dashed curve. The ratio of HCF strength to yield stress was about 0.53 again ignoring the low value of 0.47 for the β processed condition at a yield stress of 1060 MPa and a HCF strength of 500 MPa. In the high yield stress region above 1200 MPa the three curves deviated from each other, the bi-modal microstructure exhibited a much higher HCF strength as compared to the β annealed and β processed conditions clearly demonstrating the beneficial effect of a short slip length on fatigue crack nucleation. The fatigue cracks nucleated in all specimens at the specimen surface involving a β grain boundary, i.e. the soft zone adjacent to the continuous α layer.

In summary, at yield stress values > 1300 MPa, the bi-modal microstructure exhibits a higher tensile ductility, a higher HCF strength, and even a slightly higher fracture toughness as compared to β annealed and β processed microstructures of Ti-6246. This general trend should also be valid for other β titanium alloys in which the fracture related properties are adversely affected by the presence of soft zones adjacent to α layers at β grain boundaries.

7.4.2 Optimization of Properties of Ti-5553

The new β titanium alloy Ti-5553 (Ti-5Al-5V-5Mo-3Cr) is a modification of the old Russian alloy VT22 (Ti-5Al-5V-5Mo-1Cr-1Fe) [7.27]. The β transus temperature of Ti-5553 is about 860°C. The advantage of this alloy as compared to other β titanium alloys, e.g. Ti-10-2-3, is the sluggish precipitation kinetics of the α phase. Therefore, this new alloy can be used in thick section forgings for high strength airframe components [7.28], e.g. landing gear, flap tracks, etc. Both Boeing [7.28, 7.29] and Airbus are evaluating this alloy for application in structural components of future aircraft [7.30]. The effect of various heat treatments on the microstructure has been reported elsewhere [7.31] for the β annealed and bi-modal types of microstructure. Based on the discussion in Sect. 7.2.1, it is not advisable to use the β processed condition for airframe components with complex geometry and multi-axial loading. This is because of the anisotropy in properties due to the pancake shaped β grain structure and the grain boundary α layers that result in soft zones adjacent to them.

Examples of the microstructure in the vicinity of β grain boundaries for the Ti-5553 alloy are shown in Fig. 7.49. These micrographs show the continuous α layers (labeled A) along β grain boundaries, the adjacent precipitate free (soft) zone of β phase (B), and the α plate structure in the matrix (C). The regular spaced parallel lines within the soft zone visible in the transmission electron micrograph in Fig. 7.49a are a thin foil artifact (see Sect. 3.9.2.1) and the presence of those lines is a proof that the soft zone is β phase. The continuous interface between the α layer and the soft zone can be seen clearly in Fig. 7.49b. The width of the soft zone is about 0.5 μm in these examples.

In a joint development program (Otto Fuchs KG, Meinerzhagen; Airbus Germany, Bremen; Timet, France; and TU Hamburg-Harburg) the microstructure of Ti-5553 was optimized by thermo-mechanical treatments to produce a good balance of tensile ductility, fracture toughness, and HCF strength at a minimum yield
stress of 1000 MPa \[7.32\]. As discussed above, a \(\beta\) processed condition was not taken into serious consideration for this airframe application. Instead, the emphasis was placed on \(\beta\) annealed and bi-modal structures. Earlier results obtained for Ti-6246 in the low yield stress regime (see Sect. 7.4.1) showed that the fine grained (20 \(\mu\)m) bi-modal structure had high tensile ductility and high HCF strength but low fracture toughness. By comparing these properties to those of the \(\beta\) annealed material, it was concluded that the 20 \(\mu\)m grain size would be too small for an optimization of the mechanical properties including fracture toughness. Consequently, the thermo-mechanical treatment used for the bi-modal microstructure (\(\alpha+\beta\) processing and \(\alpha+\beta\) recrystallization, see Sect. 7.1.4) was selected to create medium-sized \(\beta\) grains. The two microstructural conditions which were finally compared are shown in Fig. 7.50. The \(\beta\) annealed structure had a grain size of about 400 \(\mu\)m (Fig. 7.50a) and the bi-modal structure exhibited a \(\beta\) grain size of about 125 \(\mu\)m (Fig. 7.50b). For the latter micrograph polarized light was used to ensure that large angle boundaries were present in the grain structure of the bi-modal structure.

![Fig. 7.49](image1.png)

Fig. 7.49. Continuous \(\alpha\) layer (A), adjacent precipitate free zone of \(\beta\) phase (B), and matrix \(\alpha\) plate structure in \(\beta\) titanium alloy Ti-5553, TEM

![Fig. 7.50](image2.png)

Fig. 7.50. Grain structure in Ti-5553, LM: (a) \(\beta\) annealed condition (b) Bi-modal condition, polarized light image