2
Beta Titanium Alloys

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2.1
Introduction

Beta titanium alloys are the most versatile class of titanium alloys. They offer the highest strength to weight ratios and very attractive combinations of strength, toughness, and fatigue resistance at large cross sections. Some of the disadvantages compared to $\alpha+\beta$ alloys are increased density, a rather small processing window, and higher cost (Tab. 2.1). The development and use of beta alloys since the 1950's has been well described in the literature [1, 2], the alloys are summarized in Tab. 2.2 [1].

In the past Ti-13V-11Cr-3Al had been applied to a larger extent (SR-71 Project). Currently five alloys are mainly used: Ti-10-2-3, Beta C, Ti-15-3, TIMETAL 21S, and BT 22 [3] for structural components, and Ti 17 for gas turbine engine compressor discs. Among these alloys, Ti-10-2-3 offers, when properly processed, the best combinations of strength, toughness, and high cycle fatigue strength of any

Tab. 2.1 Advantages and disadvantages of beta titanium alloys [3].

Advantages	*Disadvantages*
– high strength-to-density ratio	– high density
– low modulus	– low modulus
– high strength/high toughness	– poor low and high temperature properties
– high fatigue strength	– small processing window (some alloys)
– good deep hardenability	– high formulation cost
– low forging temperature	– segregation problems
– strip producible – low-cost TMP* (some alloys)	– high springback
– cold formable (some alloys)	– microstructural instabilities
– easy to heat treat	– poor corrosion resistance (some alloys)
– excellent corrosion resistance (some alloys)	– interstitial pick up
– excellent combustion resistance (some alloys)	

* TMP: thermomechanical processing

Titanium and Titanium Alloys. Fundamentals and Applications.
Edited by Christoph Leyens, Manfred Peters
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ISBN: 3-527-30534-3

Tab. 2.2 Composition, category, applications, source and year of introduction of major beta titanium alloys [2].

Alloy composition	*Commercial name*	*Category*	*Mo-Eq u.*	*Actual and potential applications*	*Introduction Year-by*
Ti-35V-15Cr	Alloy C	beta	47	burn-resistant alloy	90-P & W
Ti-40Mo		beta	40	corrosion resistance	52-RemCru
Ti-30Mo		beta	30	corrosion resistance	52-RemCru
Ti-6V-6Mo-5.7Fe-2.7Al	TIMETAL 125	metastable	24	high-strength fasteners	90-TIMET
Ti-13V-11Cr-3Al	B 120 VCA	metastable	23	airframe, landing gear, springs	52-RemCu
Ti-1Al-8V-5Fe	1-8-5	metastable	19	fasteners	57-RMI
Ti-12Mo-6Zr-2Fe	TMZF	metastable	18	orthopedic implants	92-Howmedica
Ti-4.5Fe-6.8Mo-1.5Al	TIMETAL LCB	metastable	18	low cost, high strength alloy	90-TIMET
Ti-15V-3Cr-1Mo-0.5Nb-3Al-3Sn-0.5Zr	VT 35	metastable	16	high strength airframe castings	na*-Russia
Ti-3Al-8V-6Cr-4Mo-4Zr	Beta C	metastable	16	oil fields, springs, fasteners	69-RMI
Ti-15Mo	IMI 205	metastable	15	corrosion resistance	58-IMI
Ti-8V-8Mo-2Fe-3Al	8-8-2-3	metastable	15	high strength forgings	69-TIMET
Ti-15Mo-2.6Nb-3Al-0.2Si	TIMETAL 21S	metastable	13	oxidation/corrosion resistant, TMCs	89-TIMET
Ti-15V-3Cr-3Sn-3Al	15-3	metastable	12	sheet, plate, airframe castings	78-USAF
Ti-11.5Mo-6Zr-4.5Sn	Beta III	metastable	12	high strength	69-Crucible
Ti-10V-2Fe-3Al	10-2-3	metastable	9.5	high strength forgings	71-TIMET
Ti-5V-5Mo-1Cr-1Fe-5Al	VT 22	metastable	8.0	high strength forgings	na*-Russia
Ti-5Al-2Sn-2Zr-4Mo-4Cr	Ti-17	beta-rich	5.4	high strength, medium temperature	68-GEAE
Ti-4.5Al-3V-2Mo-2Fe	SP 700	beta-rich	5.3	high strength, SPF	89-NKK
Ti-5Al-2Sn-2Cr-4Mo-4Zr-1Fe	Beta-CEZ	beta-rich	5.1	high strength, medium temperature	90-CEZUs
Ti-13Nb-13Zr		beta-rich	3.6	orthopedic implants	92-Smith & N.

* na: not announced

titanium alloy. Recently some new alloys like Beta-CEZ, LCB, and SP 700 have been developed and are now being introduced. More information about the particular use of these alloys will be given later.

One of the keys for successful application of beta alloys is the development of appropriate processing conditions. Systematic correlations between processing, microstructure, and properties must be derived in order to find a technically reasonable and safe processing window. Questions beyond these issues, in particular concerning the corrosion behavior, alloy development, applications, etc., are described in more detail elsewhere [1, 2].

Subsequently, a brief introduction to the metallurgy and processing of beta titanium alloys will be given. Then, an attempt will be made to describe the effects of deformation and heat treatment on microstructure and on the main properties like tensile values, toughness, high cycle fatigue (HCF), and fatigue crack propagation (FCP).

2.2 Metallurgy and Processing

A beta alloy is defined here as a titanium alloy with sufficient β-stabilizer content to suppress the martensitic transformation during quenching to room temperature. This means that 100% beta phase is retained (Fig. 2.1). The beta stability can

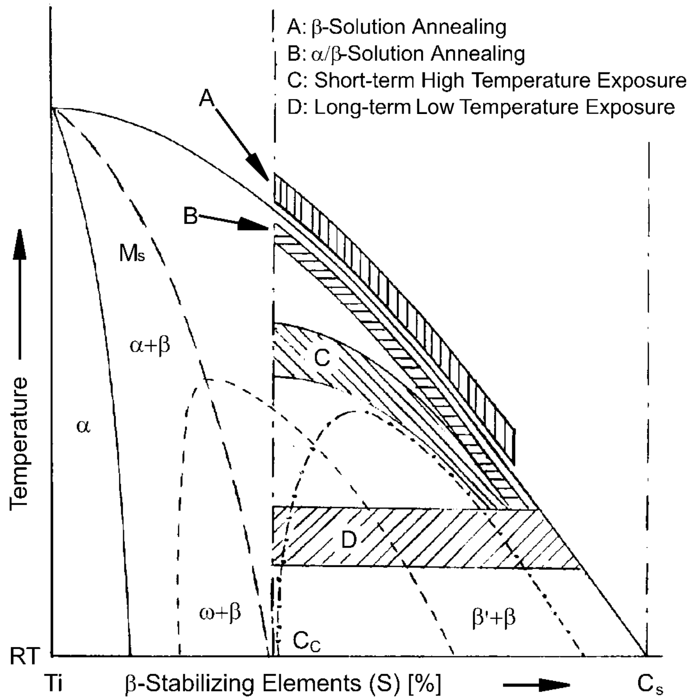


Fig. 2.1 Schematic phase diagram of metastable beta alloy [9].

be described by the molybdenum equivalent, which combines the effects of the various β-stabilizing elements like Mo, V, Fe, Cr, Nb, etc. [3]. A minimum value of about 10% is necessary to stabilize the beta phase during quenching (see Mo equivalent in Tab. 2.2). Beyond a β-stabilizer concentration of c_s, stable β alloys exist (Fig. 2.1). Between the minimum concentration, c_c, and c_s alloys are metastable; most commercial β alloys fall into this range (Tab. 2.2).

With the help of Fig. 2.1 and a qualitative TTT-diagram of Ti-10-2-3 in Fig. 2.2 [4, 5], the development of the basic microstructures will be explained briefly; more comprehensive descriptions are given in [6, 7].

Processing of β alloys usually consists of a hot working operation followed by a heat treatment. The final hot working step is normally performed in the α+β field for the leaner beta alloys, and preferentially in the β field for the richer beta alloys. The heat treatment consists of a solution treatment followed by quenching and a subsequent aging treatment. A solution heat treatment above the β-transus temperature results in coarse β grains (Fig. 2.3a). Solution treating slightly below the β transus leads to the precipitation of primary α (α_p) (Fig. 2.3b and c). The heat treatment temperature controls the α_p volume fraction, while forging and rolling deformation influences the α_p shape. Without working a needle-like α_p shape develops; an increased amount of hot working leads to a globular α_p shape.

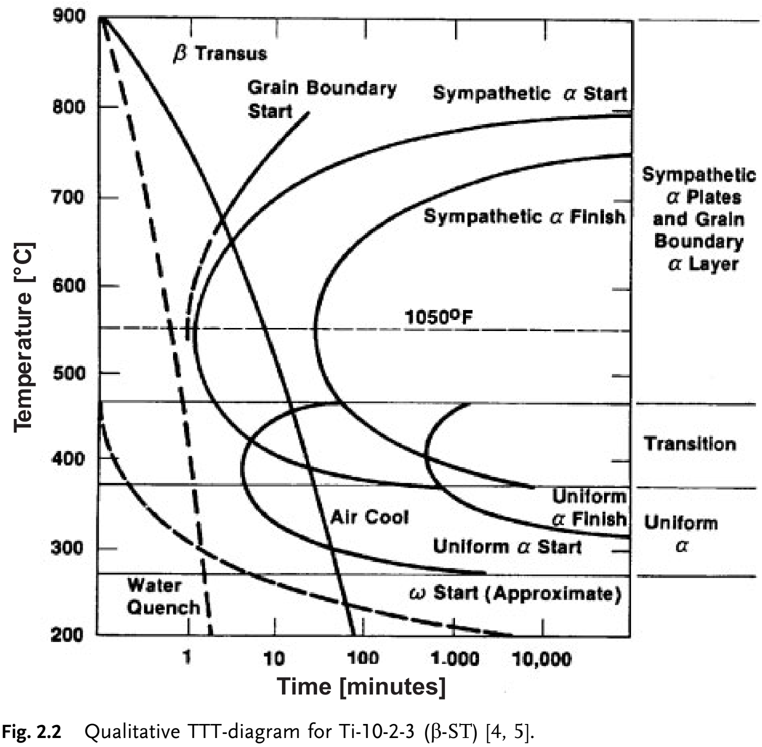


Fig. 2.2 Qualitative TTT-diagram for Ti-10-2-3 (β-ST) [4, 5].

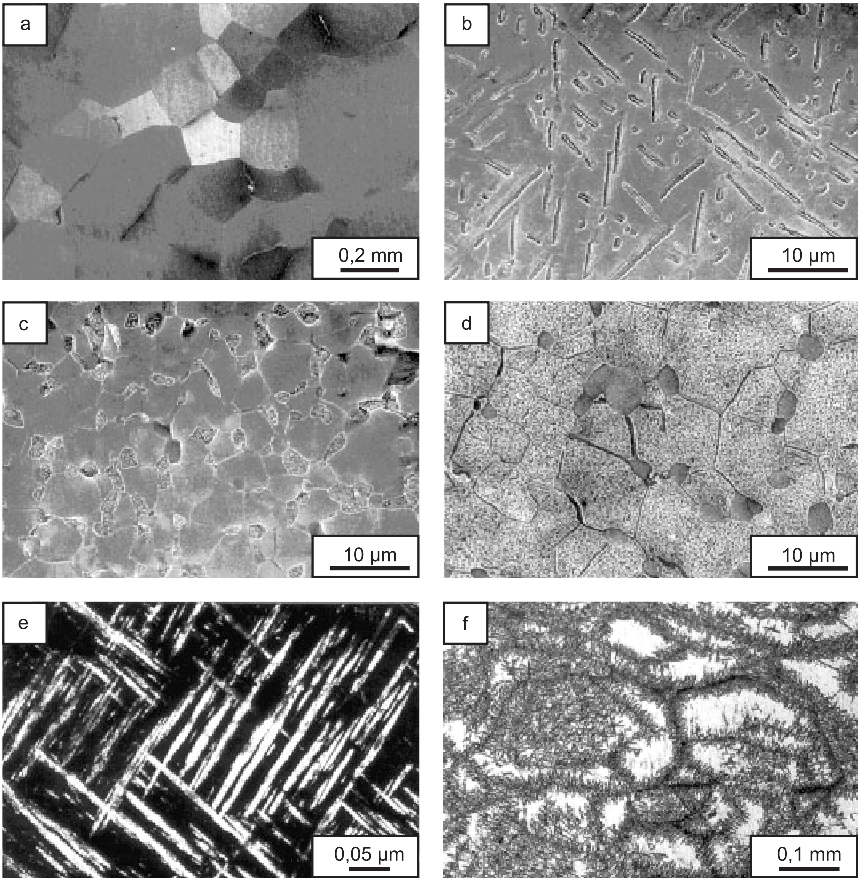


Fig. 2.3 Different microstructures of beta alloys; (a)–(e): Ti-10-2-3; f: Beta C); (a) β-ST and aged; (b) 10% elongated α_p; (c)10% globular p; (d) 10% α_p (recrystallized) with GB-α; (e) secondary α (TEM); (f) inhomogeneous precipitation of secondary α.

The β grain size and size distribution are controlled by a proper selection of temperatures and deformation starting from ingot breakdown [8]. Several cycles of deformation and recrystallization are possible if small grain sizes are required.

Grain boundaries are preferred sites for a film-like α precipitation during forging, cooling from β-forging, and heat treatment. The precipitation of detrimental grain boundary α can be suppressed by rapid cooling from the β phase field. Since this is impossible to realize as, for example, in the case of large cross sections, subsequent α/β-processing can break up the grain boundary film (Figs. 2.2 and 2.3 d).

At lower temperatures, typically 400 °C to 600 °C, the secondary α (α_s) precipitates in a fine distribution (Fig. 2.3 e and 2.3 f). It has a significant strengthening effect depending on its volume fraction and size, which in turn are controlled by aging temperature and time as well as by the solution treatment temperature [6]. The precipitation of α_s can be homogeneous as it is found in lean beta alloys like Ti-10-2-3, or inhomogeneous in richer beta alloys, like Beta C or Ti-15-3. In the latter case, precipitation starts from grain boundaries and later in the grain leaving some local areas unaged (Fig. 2.3 f). Cold work generally enhances the aging response and can lead to a more homogenous distribution of the α_s [9]. The uniformity of the α_s can also be influenced by step aging procedures as will be discussed later. In lean alloys coherent ω phase can precipitate at low temperatures (Fig. 2.2). It will not be discussed further since it is not used due to its embrittling effect [4]. Alloys with a high amount of β-stabilizer can form intermetallic compounds. Their possible effect on properties is discussed in [6, 7].

In summary, the following microstructural constituents are important for property control of beta titanium alloys:

- β grain size
- α_p and α_s including their shape, size, and volume fraction
- grain boundary α.

2.3 Mechanical Properties

2.3.1 Tensile Properties

Through aging, a wide range of yield stresses (typically 900 to 1400 MPa) can be reached in beta titanium alloys. With increased aging, however, all β alloys show a significant reduction in ductility. This is illustrated for Ti-10-2-3 in Fig. 2.4 where the elongation to fracture is plotted versus the yield strength. This observation has been explained as an increased strain localization in the aged matrix and by a higher yield stress difference between the soft primary α and the aged β matrix, which leads to early crack nucleation (Fig. 2.5) [10]. In more highly β-stabilized alloys like Ti-15-3 or Beta C, with an inhomogeneous α_s precipitation, duplex aging procedures have been developed. They consist of "high/low"- or "low/high" aging sequences. Duplex aging allows, for example, higher strength in shorter time than single-step aging [9, 11, 12]. Some authors also claim an improvement in ductility [11], while others do not find an effect on ductility [12, 13]. Duplex aging was mainly developed for an improvement of toughness and fatigue resistance and will be further discussed in that context.

Besides the dominating effect of aging, primary α (α_p) can also influence ductility. As described in section 2.2, processing influences both the shape and size of α_p. A coarsening of the α_p as well as a change from globular to acicular α_p leads to a reduction in ductility in Ti-10-2-3, as shown in Fig. 2.4 [10, 14]. The reason for both observations is the increased "effective" size or slip length of the soft α_p favoring early crack nucleation [10, 15]. An increase in the volume fraction of α_p

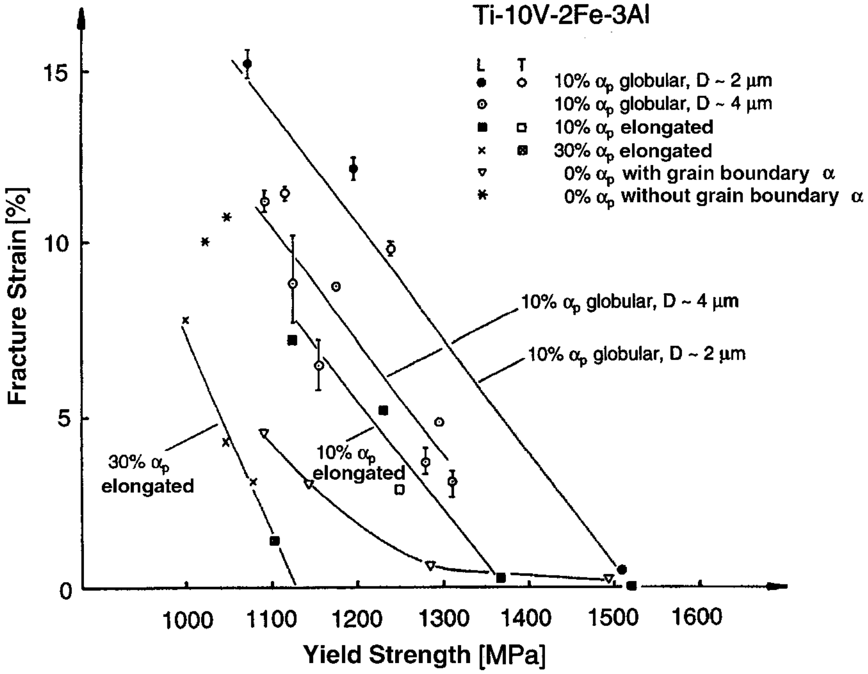


Fig. 2.4 Elongation to fracture versus yield strength for different microstructures in Ti-10-2-3.

(lower solution heat treatment temperatures) leads to a reduced ductility at constant macroscopic yield strength (Fig. 2.4, 10% α_p versus 30% α_p). In order to achieve a comparable yield stress, the β of the microstructure with a higher volume fraction of soft α_p must be aged higher, which in turn favors crack nucleation [10, 15]. At a constant aging treatment an increase in the α_p volume fraction reduces yield strength and increases ductility, as shown in Tab. 2.3 [4, 10, 16].

The effects of grain size and grain boundary are interrelated. These parameters do not affect strength [17], but can have a pronounced effect on ductility. The presence of grain boundary α, especially as a continuous film, lowers ductility since the strain is localized in the soft α film leading to crack nucleation and fracture at grain boundaries (Fig. 2.4, 2.5 c and d) [6, 10, 16, 17, 18]. For alloys Ti-10-2-3, Ti-15-3, and Beta C, a grain refinement has been shown to improve ductility (Fig. 2.6) [17, 19, 20, 21]. In cases where crack nucleation occurs at grain boundary α, this observation can be explained by a reduced slip length in the soft film resulting in delayed crack nucleation. If crack nucleation is intergranular, there is no conclusive explanation for a grain size effect on ductility. A summary of the effects of the various microstructural parameters on tensile properties is given in Tab. 2.4.

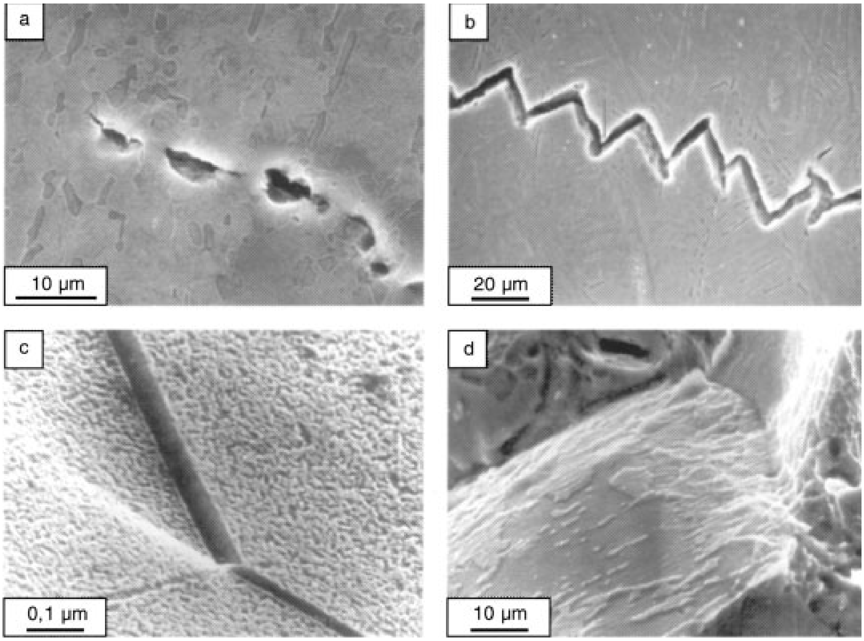


Fig. 2.5 (a), (b): Increased matrix aging leading to localization of slip [15]; (a) YS = 1100 MPa; (b) YS = 1400 MPa; (c), (d): Preferential plastic deformation in grain boundary α; (c) [10] leading to grain boundary fracture (d).

Tab. 2.3 Yield strength, K_{Ic}, and true fracture strain for two volume fractions of α_P at constant aging treatment for Ti-10-2-3 [15].

α_p volume fraction [%]	*Yield Strength [MPa]*	*K_{Ic} [MPa]*	*F*
10	1402	20	0
30	1101	34	0.04

2.3.2 Fracture Toughness

Increased aging significantly reduces fracture toughness. This has been shown for various beta alloys [13, 15, 20, 22, 23], an example is given for Ti-10-2-3 in Fig. 2.7. Fractography has revealed that as for ductility, an increased strain localization and increased strength difference between the soft α_p and the aged matrix is the reason for this trend [15]. Therefore, because of the same micromechanisms of fracture both properties show the same trend. Duplex aging has been tried in order to increase the strength and toughness compared to single-step aging [12, 13, 23, 24]. The results indicate that a low/high aging combination improves the

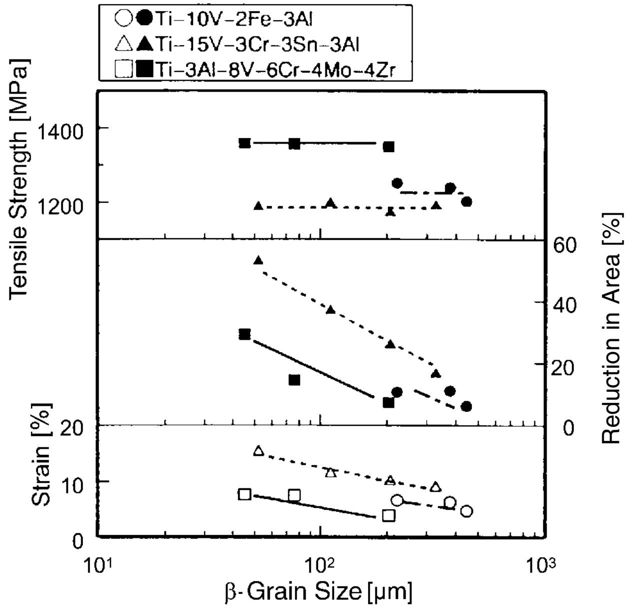


Fig. 2.6 Effect of β grain size on tensile properties of three commercial beta alloys aged at 500 °C for 8 hrs [17].

Tab. 2.4 Effect of microstructure parameters on properties of Ti-10-2-3.

Microstructure	***El (RA)***	***K_{Ic}***	***HCF***	***FCP (threshold region)***
Secondary α($α_s$)				
– increasing volume fraction YS ↑	–	–	+	○ (–)
decreasing size YS ↑	–	–	+	○ (–)
– inhomogeneous distribution (e.g. preferential formation at grain boundaries)			–	○
Primary α($α_p$)				
– volume fraction: increasing (10% → 30%)	–	–		○
YS = constant				
aging treatment constant (YS ↓)	+	+		
– morphology: (globular → elongated)	–	+		○ (+)
– size: (e.g. 2 μm → 4 μm)	–	○		○
Grain boundary α(GBα)	–	○ (–)	–	○
β grain size: (large → small)	+			○
transgranular fracture		○		
intergranular fracture	○ (+)	+/–	+	

El (RA): Elongation to fracture (reduction in area); K_{Ic}: Fracture toughness; HCF: High cycle fatigue; FCP: Fatigue crack propagation; +: improvement; –: deterioration; ○: no effect toughness of Ti-10V-1Fe-1Cr-3Al [12], but has no effect on the toughness of Beta C [13, 24]. For Ti-15-3, a high/low combination appears to be more successful on improving the toughness [23]. The toughness increase, from about 43 MPa $m^{1/2}$ to 66 MPa $m^{1/2}$, when using duplex aging instead of single aging on Ti-15-3 is considerable. The investigation showed that a mixture of coarse, long primary α ("high aging") and fine secondary α ("low aging") was able to cause a more tortuous crack path increasing the toughness by this geometrical effect.

The role of primary α (α_p) on toughness has been studied in numerous investigations [8, 14, 15, 20, 21, 25]. For example, if the α_p shape changes from elongated to globular toughness will decrease (Fig. 2.7) [14, 15]. Fractographic examination has shown that elongated α_p leads to a more pronounced crack deviation [15]. An increase of the α_p volume fraction has been shown to drastically reduce toughness when comparing at constant yield strength (Fig. 2.7). The same reason largely applies for this effect as for ductility, namely an increased degree of matrix aging is compensating for the higher amount of soft α_p [15]. When comparing at constant aging, an increase in the α_p volume fraction leads to an increase in toughness (Tab. 2.3).

Several authors have studied the role of grain size and grain boundary α [15, 17, 19, 20, 22, 26, 27]. A beta grain refinement has been found to reduce the frac-

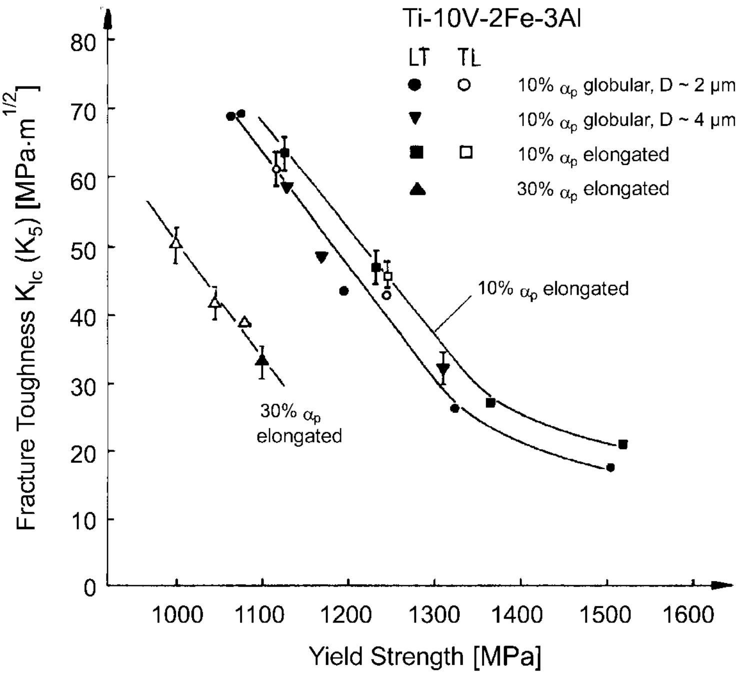


Fig. 2.7 Fracture toughness versus yield strength for different microstructures with primary α phase in Ti-10-2-3 [15].

ture toughness of Ti-15-3 [17, 28]; while for Beta C and Ti-10-2-3 no effect was found (Fig. 2.8) [17, 19].

Grain boundary α has been claimed to decrease [15, 27] or increase [29] fracture toughness or not to effect it [15]. Examples are shown in Fig. 2.9 where fracture toughness is plotted versus yield strength. Comparing two microstructures with and without primary α (β-ST, DA), and with a grain size of 300 μm, there is no influence of grain boundary α on toughness. For a microstructure with primary α and very small, recrystallized grains that are decorated with grain boundary α (Fig. 2.3 d), then the fracture toughness drops drastically compared to the microstructure with large grains (β-ST).

In order to explain observations that appear contradictory, it is necessary to take into account the degree of aging, plastic zone size, and stress state in addition to grain size and grain boundary α (Fig. 2.10) [15, 20]. The subsequent conclusions can be seen as a further development of an earlier model by Williams et al. [25] that treats the grain boundary α as a low energy fracture path by plastic zone confinement to this soft film.

(1) If the plastic zone is much smaller than the grain size (high strength, large grain) the fracture will start from the transgranular pre-fatigue crack [15]. For this fracture mode grain boundary α will not affect fracture toughness as has been shown on Ti-10-2-3 [15, 20], since the intrinsic toughness of the aged matrix is measured (Fig. 2.9, compare β-ST and DA).
(2) If the plastic zone size is much larger than the beta grain size (small grain, low strength), cracks can initiate and proceed in the soft grain boundary α

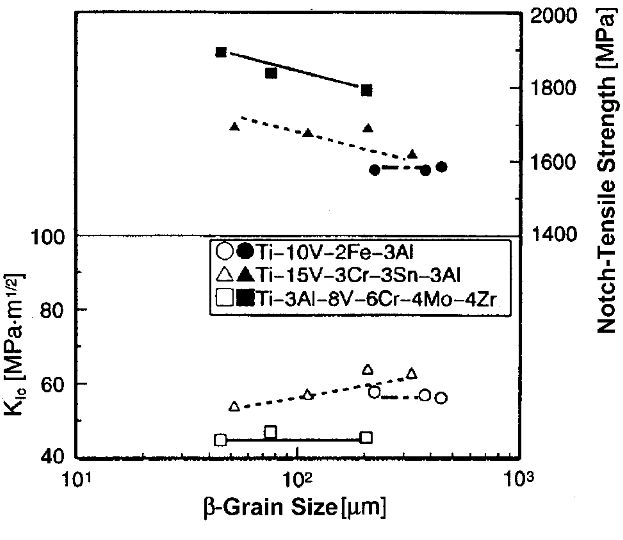


Fig. 2.8 Effect of β grain size on notched tensile strength and fracture toughness of three commercial beta alloys aged at 500 °C after ref. [17].

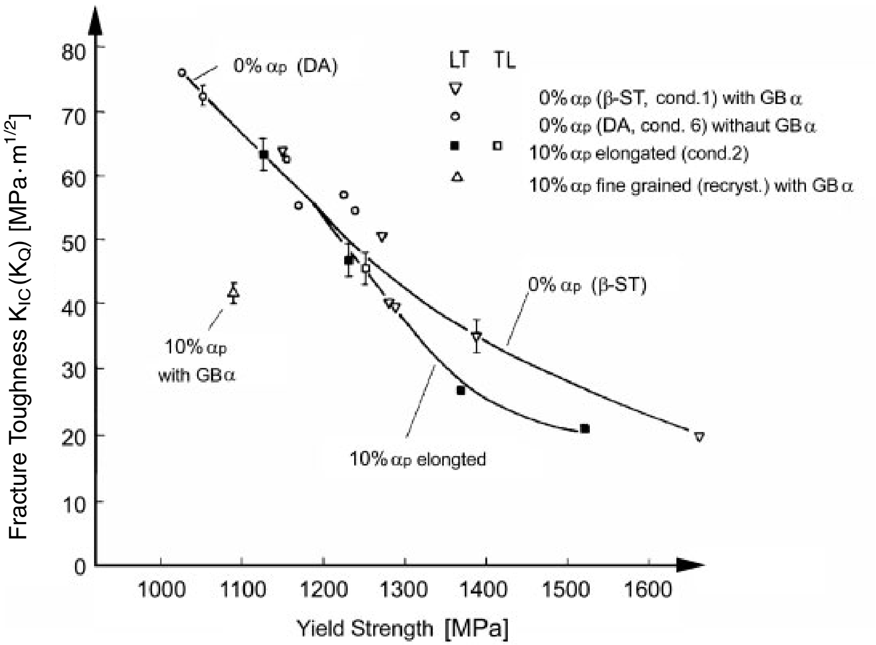


Fig. 2.9 Fracture toughness versus yield strength in Ti-10-2-3, influence of grain boundary α phase and grain size [15].

which can be regarded as a low energy path [15, 22, 25]. At constant yield stress, fracture toughness will be smaller than for the transgranular fracture [15] (Fig. 2.9, compare β-ST and 10% α_p with grain boundary α). As long as the grain boundary fracture mechanism is active, an increasing grain size should increase toughness since more tortuosity of the crack path is created which, as a geometrical effect, increases toughness. This mechanism has been used in an improved manner for the development of alloy Beta-CEZ. Instead of a continuous grain boundary α film, a broken up grain boundary α ('necklace') has been produced, which still deflects the crack but is a higher energy path and does not reduce ductility [27, 29]. In addition, in the case of intergranular fracture, an increase in matrix aging will lead to a stronger confinement of the plastic zone to the soft grain boundary α film thus leading to a lower toughness [25]. In the case of stretched grains, for example by forging, intergranular fracture and the crack deviation effect can lead to a pronounced anisotropy in fracture toughness.

(3) If no grain boundary α is present, toughness should be independent of beta grain size, since fracture will advance transgranularly.

In summary, using this approach it is possible to explain seemingly contradictory results (Tab. 2.4, Fig. 2.10). An optimum toughness is given by a combination of a

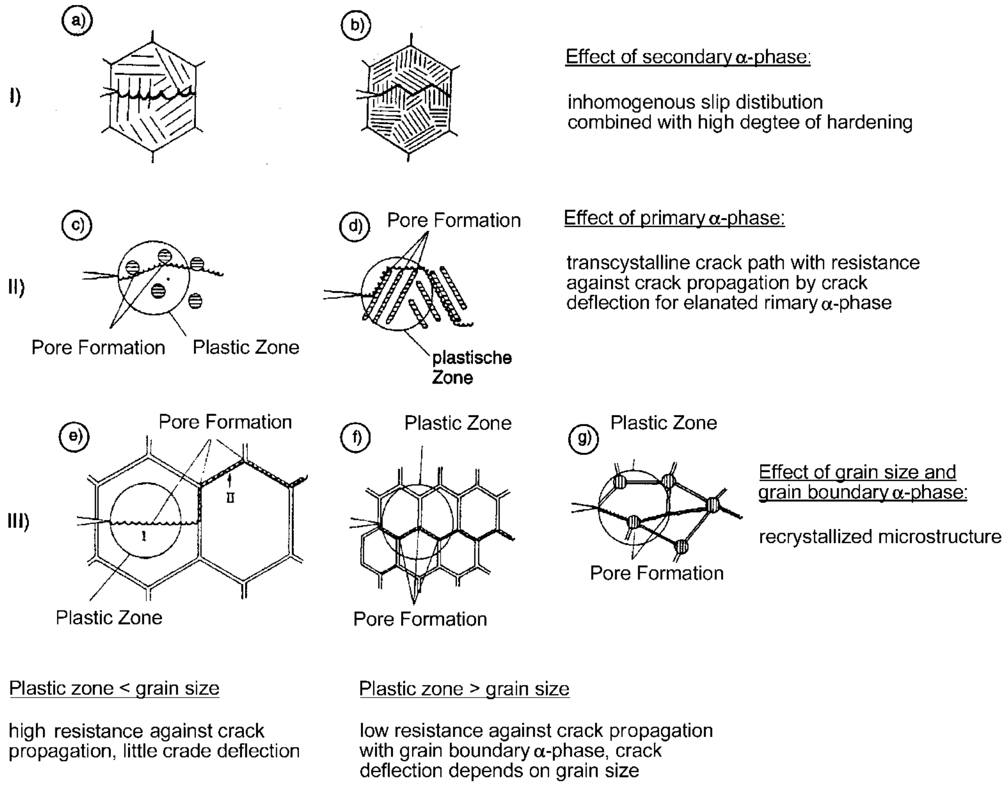


Fig. 2.10 Schematic illustration of crack initiation and growth in beta alloys.

high energy crack path and maximum crack deviation. One such combination is an aged matrix with acicular α_p (example Ti-10-2-3), another possibility is a broken up grain boundary α with a large grain size (example Beta-CEZ).

2.3.3
Fatigue (HCF)

The good fatigue potential of beta alloys has been known for quite some time [30]. A high cycle fatigue strength (HCF) around 700 MPa ($R=-1$, $K_t=1$) can be achieved in Ti-10-2-3 for large cross sections ($\geq$100 mm); this is not possible for any other titanium alloy. New fatigue critical applications in the aerospace industry [31] have triggered some recent research efforts to understand and optimize the fatigue behavior. Boyer and Hall [22] as well as Jha and Ravichandran [32] have reviewed the effects of various thermomechanical treatments on fatigue along with the corresponding microstructures. Subsequently, their discussions will be briefly summarized, and some recent results will be added and discussed.

An increase in aging, or 0.2% yield strength, can increase HCF strength. This effect has been observed for example in Ti-10-2-3 [5, 33, 34], Beta C [35], Ti-15-3

[28, 36], and SP 700 [37]. Fig. 2.11 shows the HCF strength for various beta alloys as a function of yield strength at R=0.1. Similar results have been obtained for R=–1. From the data it appears that the richer beta alloys like Beta C or Ti-15-3 have a lower fatigue strength level than the leaner alloys such as Ti-10-2-3 or SP 700. One possible reason may be the trend for an inhomogeneous precipitation of α_s in the richer alloys. Gregory et al. have shown that for Beta C crack nucleation occurs in the transgranular precipitate-free regions [35]. Using a duplex aging procedure a more homogeneous α_s precipitation resulting in a 50 MPa increase in fatigue strength was achieved (Tab. 2.5).

From this work (Fig. 2.11, Tab. 2.5) it also appears that an upper limit exists for HCF strength that cannot be exceeded by further aging. It can be concluded that the soft regions, like grain boundary α, precipitate-free zones, or primary α, where fatigue cracks initiate become more and more dominant at higher strength since the strength differential between these zones and the aged matrix becomes greater. In addition, the trend to localized slip in an aged matrix that has been observed at high strength in Ti-10-2-3 [8] may contribute to an upper limit in fatigue strength.

A grain size reduction has been shown to increase the fatigue strength of Beta C [19], Ti-10-2-3 [38], and Ti-8-8-2-3 [39]. This is illustrated in Tab. 2.6 for Beta C. Grain boundary α has been discussed as a crack nucleation site. As has been shown for static properties [15, 20], the grain size reduces the slip length of grain boundary α leading to delayed crack nucleation. The detrimental role of grain boundary α on fatigue was also shown for Ti-10-2-3 [34]. The effect of α/β defor-

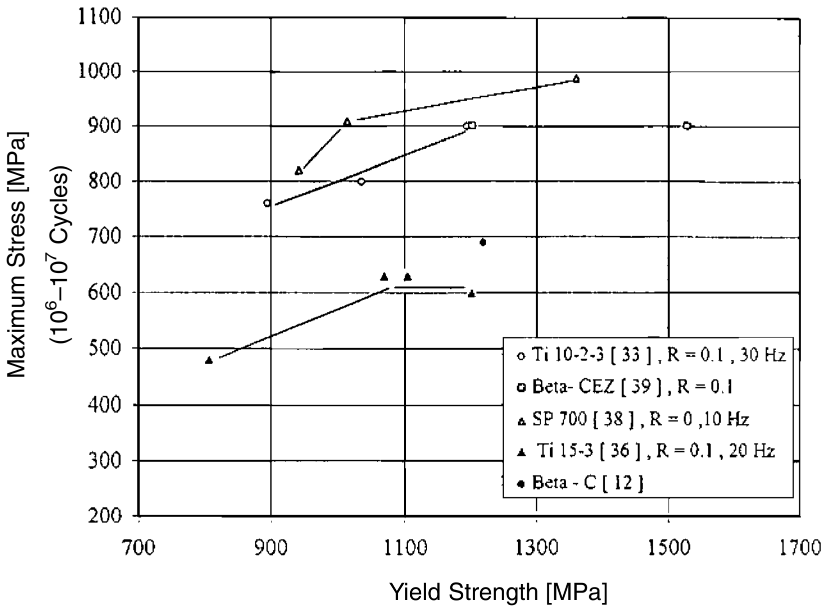


Fig. 2.11 HCF strength versus yield strength for different beta alloys.

Tab. 2.5 Effect of aging degree and duplex aging on HCF strength in Beta C [35].

Heat treatment	*YS [MPa]*	*HCF-Strength* σ_a *[MPa] at* 10^7 *cycles; R=–1,* K_t*=1*
927 °C, AC	850	390
927 °C, AC + 16 h/540 °C	1085	575
927 °C, AC + 4 h/440 °C + 16 h/560 °C	1085	625
927 °C, AC + 72 h/440 °C + 16 h/500 °C	1325	625

Tab. 2.6 Effect of grain size on HCF strength in Beta C bar, R=0,1, K_t=1 [19].

Grain size [µm]	*YS [MPa]*	*HCF-Properties* (10^6 *cycles)*	
		HCF Strength [MPa]	*HCF Strength / YS*
40	1255	815	0,65
34	1188	800	0,67
75	1220	690	0,57
122	1344	670	0,50

mation after β-forging was investigated and it was found that the purely β-forged condition showed a higher ratio of HCF strength to yield strength than the β+α/β-forged material with ≥30% α/β deformation (Fig. 2.12). While considerable amounts of grain boundary were observed in the purely β-processed condition, they were effectively removed by an α/β-deformation of ≥30%. This also explains why more than 30% α/β deformation does not further improve fatigue strength. Campagnac et al. have also observed the interdependence of HCF strength on α/β deformation in the range between 0.35 and 1.0 true strain [40]. If grain boundary α is suppressed and cracks initiate in the aged matrix, a grain size effect on HCF strength should not be expected. A summary of microstructural effects on fatigue is given in Tab. 2.4.

Although there are numerous open questions regarding the understanding and optimization of fatigue (role of primary α, notched fatigue results, etc.) the existing results already give some indications how to improve fatigue resistance: aging to an optimum level, small grain size, reduction/suppression of grain boundary α, and homogeneous distribution of secondary α.

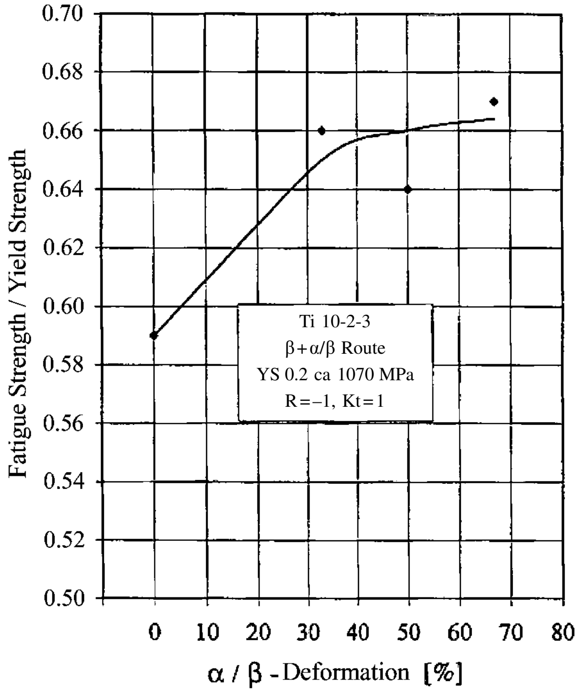


Fig. 2.12 HCF strength versus α/β forging deformation for Ti-10-2-3 [34]

2.3.4
Fatigue Crack Propagation (FCP)

In contrast to other mechanical properties, fatigue crack propagation resistance is much less sensitive to processing and microstructure and even to chemical composition of alloys [41, 42]. Fig. 2.13 shows a da/dN-ΔK plot with results on Ti-10-2-3, Ti-15-3, TIMETAL 21S, Beta C, and Beta-CEZ that are taken from several references [39, 41-45]. This figure updates an earlier comparison [42] by including new data for TIMETAL 21S and Beta-CEZ. Although quite different products and processing conditions were taken, the curves fall in a narrow band especially at intermediate da/dN values (Paris-region). Compared to mill-annealed Ti-6-4, the fatigue crack propagation rates are slightly higher at low da/dN values [42].

The influence of processing and the resulting microstructures has been particularly investigated for Ti-10-2-3 [41, 42, 46, 47], and to a lesser extent for Beta C [13], Ti-15-3 [39, 48], TIMETAL 21S [43], and Beta-CEZ [27]. Increased aging does not significantly change behavior in the threshold and Paris region for Ti-10-2-3 [42, 46], TIMETAL 21S [43], and Ti-15-3 [48]. A slightly higher fatigue crack growth rate (factor of about 2) has been found at higher strength for Beta-CEZ [27]. For Ti-10-2-3 a variety of eleven forging and heat treatment conditions has

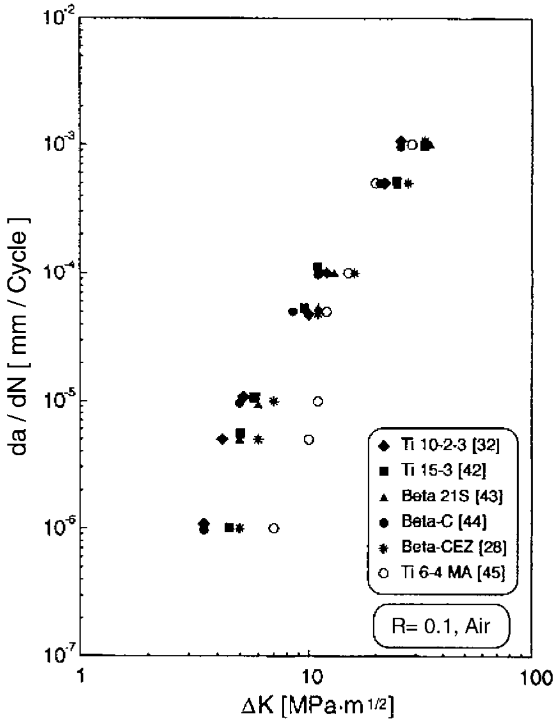


Fig. 2.13 Fatigue crack growth for different beta alloys in comparison to mill-annealed Ti-6-4.

been investigated at a nominal yield strength of 1240 MPa [41, 47]. For all the α-aged conditions very little effect of microstructure on FCP was observed (Fig. 2.14). Only one ω-aged condition, which is commercially irrelevant, showed a significantly higher threshold value. This effect is due to a change in slip distribution caused by the coherent, shearable ω particles and the resultant roughness of the crack front profile [41]. An investigation of the Russian BT 22 alloy has shown that compared to globular primary α, lamellar α increases the fatigue crack growth rate by a factor of 5 [26]. Fractographic analysis has generally shown macroscopically and microscopically rather flat and transgranular fracture surfaces [41, 42, 46]. Crack closure measurements as a function of yield stress [46] resulted in relatively small crack closures (about 1 MPa $m^{1/2}$), which are not consistently varying with yield stress.

A discussion of results must consider that the volume affected in a FCP test is very small. For example, the plastic zone size at ΔK=5 MPa $m^{1/2}$ and yield strength = 1100 MPa is on the order of 1–2 μm. Therefore, it encompasses only a few α_s particles and the crack will grow by a local decohesion of α_s/β interfaces. The α_s precipitates as a dominating parameter probably do not vary sufficiently in size, shape, and volume fraction to achieve major differences in FCP. This is in contrast to α+β Ti alloys like Ti-6-4, which can be considerably influenced in fatigue crack growth. On the other hand, beta alloys are hardly inferior in fatigue

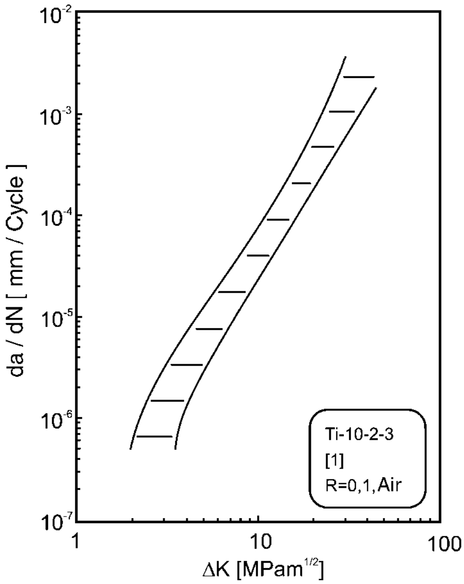


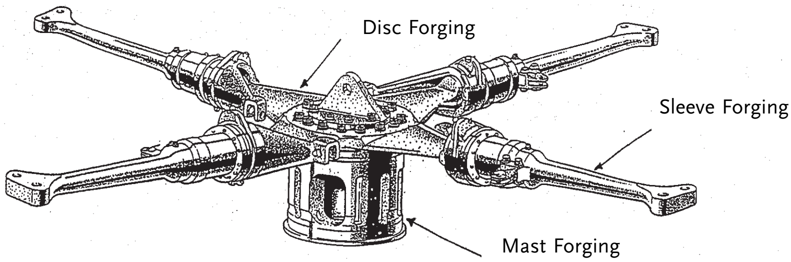
Fig. 2.14 Fatigue crack growth for eleven different microstructures in Ti-10-2-3; YS = 1240 MPa [41].

crack growth resistance. The insensitivity of FCP to microstructure gives the chance to optimize other mechanical properties without damaging FCP.

2.4 Applications

Despite the obvious potential of beta alloys, their share of the titanium market is still small (1% of the US market) [3]. However, their use is continuously increasing, especially in aerospace [31]. This is through increased use of existing alloys like Ti-10-2-3. Most of the landing gear of the Boeing 777 airplane, for example, is produced from Ti-10-2-3 forgings, including the large truck beam (see Chapter 13). In addition, Fig. 2.15 shows the rotor head of the Westland Super Lynx helicopter, which is also produced from Ti-10-2-3 instead of Ti-6-4. Ti-10-2-3 is also currently used in other helicopter programs. The driving force for selection of Ti-10-2-3 in the latter case was increased fatigue properties of the beta alloy. There are numerous other applications for beta alloys, including BT22 as a competitor to Ti-10-2-3, Ti-15-3 (sheet and castings), and TIMETAL 21S with its good high temperature properties [31].

Outside aerospace, beta alloys can be used for downhole service (deep oil and gas wells) where Beta C is a particularly appropriate candidate because of its good combination of mechanical and corrosion properties [49]. New alloys under development are: TIMETAL LCB (LCB – low cost beta) with its first application in automotive springs [3], SP 700 as a high strength alloy with improved cold and superplastic formability [37], and TMZF (Ti-12Mo-6Zr-2Fe) as a surgical implant alloy with low modulus, good strength, and corrosion resistance [51].



Courtesy of Westland Helicopters

Fig. 2.15 Super Lynx helicopter main bolted rotor head made from Ti-10-2-3.

The description of applications is by far not complete and the reader is referred to the referenced literature. But it shows that beta alloys have an excellent property potential for a wide field of applications. One particular challenge for the introduction of this alloy family is the necessity for strict process control, since some properties are very sensitive to process variations. Uniformity of properties is a major issue particularly for large parts with complex shapes since the variations in local deformation have to be controlled. The improved understanding of the relationships between processing and microstructures/properties is the necessary basis for a successful introduction of beta alloys into further applications.

2.5
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