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Effect of Beta Flecks on Low-Cycle Fatigue Properties of Ti-10V-2Fe-3Al

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The effect of beta flecks on low-cycle fatigue (LCF) properties was investigated at room temperature for a high-temperature ($\alpha + \beta$)-processed and also a β-processed Ti-10V-2Fe-3Al alloy. For both the ($\alpha + \beta$)-processed and the β-processed material, beta flecks had a significant influence on LCF and tensile properties. The materials with beta flecks showed a loss in LCF life and ductility. Larger beta flecks resulted in lower LCF life and ductility. It seemed that β-forged material contained much smaller beta flecks but had a similar detrimental effect on LCF properties as the ($\alpha + \beta$)-processed one. Based on the diffusion calculation, it could be concluded that chemical composition inhomogenieties could not be reduced by using beta forging in the 820 °C β region. Extensive light microscopy and scanning electron microscopy (SEM) observations showed that beta flecks were susceptive to crack nucleation and propagation.

Keywords beta flecks, intergranular cracking, low-cycle fatigue, Ti-10V-2Fe-3 Al alloy

1. Introduction

The Ti-10V-2Fe-3Al alloy (hereafter designated as Ti-10-2-3) is a near-beta titanium alloy. It is quite attractive for commercial use because of its combination of strength, hardenability, ductility, and toughness.[1,2] Due to increased additions of beta stabilizing elements, namely, vanadium and iron, a melt process segregation problem called "beta flecks" can be encountered for large-ingot materials. The beta flecks are defined as segregated volumes in an ingot having relatively large localized concentrations of beta stabilizing elements. It has been generally accepted that beta flecks of Ti-10-2-3 are caused primarily by local concentration of iron.[3,4]

There has been a great deal of attention given to Ti-10-2-3 and other titanium alloys in fatigue critical applications, and despite this, very little has been done to correlate beta flecks to mechanical properties.[5-11] Rüdinger and Fisher have shown no adverse effect of beta flecks on properties such as tensile, high-cycle fatigue and low-cycle fatigue (LCF) in the annealed condition.[5] However, a loss in fatigue properties was observed in Ti-17 and Ti-10-2-3 alloy processed in the elevated $\alpha + \beta$ region.[4,6] Our preliminary studies have also shown beta flecks had a detrimental effect on ductility and LCF.[7,8,9]

The purpose of this investigation was to examine the LCF of the alloy in the $\alpha + \beta$-forged and β-forged conditions. Microstructural examinations and fractography were also carried out, so that a correlation between beta flecks and mechanical properties could be established.

2. Materials and Procedures

The Ti-10-2-3 alloy used in this investigation was received in the form of 70 mm diameter rolled bar containing profuse beta flecks. The chemical composition is given in Table 1 in comparison to BMS7-260B.[10]

To evaluate the effect of different forging technologies on beta flecks, $\alpha + \beta$ forging and β forging were used. The $\alpha + \beta$ processed material had been forged at 770 °C, solutionized at 780 °C for 2 h, water quenched, aged at 520 °C for 8 h, and air cooled. The β-processed material had been forged at 820 °C, solution treated at 760 °C for 2 h, water quenched, aged at 520 °C for 8 h, and air cooled.

The LCF specimens were machined from $\alpha + \beta$-forged and β-forged materials. Most of the LCF tests were performed on cylindrical specimens with a diameter of 5 mm and a gauge length of 25 mm. The other LCF specimens were machined into plates, so that beta flecks could be more evident. The LCF tests were accomplished on a MAYES testing machine (Hongyuan Forging and Casting Co., Sanyuan, Shaanxi, China) at an R ratio of 0.1 and a cyclic frequency of 15 Hz.

Optical metallography was carried out on the fractured specimens polished by standard methods. The specimens for metallographic examination were etched in a solution of 8 mL HF, 10 mL HNO_3, and 82 mL H_2O. The fractography was carried out by JSM-35C scanning electron microscopy (Northwestern Polytechnical University, Xi'an, China).

Table 1 Chemical Compositions of Ti-10V-2Fe-3Al Alloy

Alloy element	Al	V	Fe	Si	C	N	H	O	Ti
Concentration (wt. %)	3.05	10.23	2.08	<0.05	0.015	0.014	0.02	0.013	Bal
Requirements according to BMS7-260B	2.6–3.4	9.0–11.0	1.7–2.2	0.10	0.05	0.05	0.015	0.13	Bal

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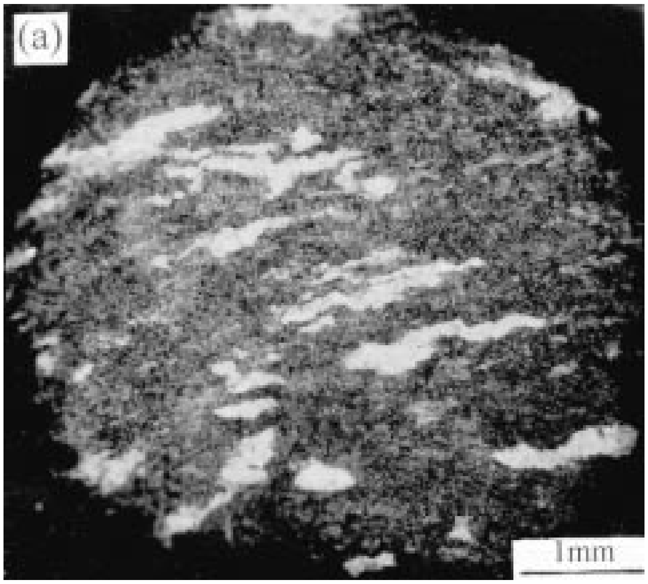
3. Experimental Results

3.1 Microstructure

In order to correlate beta flecks and LCF, one-half of a fractured specimen was prepared for microstructure evolution, and the other half was used for fractography and chemical composition measurement. Being resistant to etching, beta flecks were bright strips or bright blocks in macrographic examination, as shown in Fig. 1. The usual microstructure of $\alpha+\beta$-forged specimens consisted of equiaxed α particles in an aged β matrix (Fig. 2a), while β flecks contained few or no equiaxed phases, indicating the lowering of B transus due to the enrichment with β stabilizing elements. Extremely large beta grains (about 200 μm) were then developed locally due to the absence of α to restrict grain growth. It is difficult to distinguish beta flecks from the usual aged matrix in the β-forged condition, because both of them contained a microstructure with a large former β grain size and α plates (Fig. 2c and d). It was noted that beta flecks contained a much coarser β grain in which α plates were indistinct because of resistance to etching and, accordingly, were readily detectable.



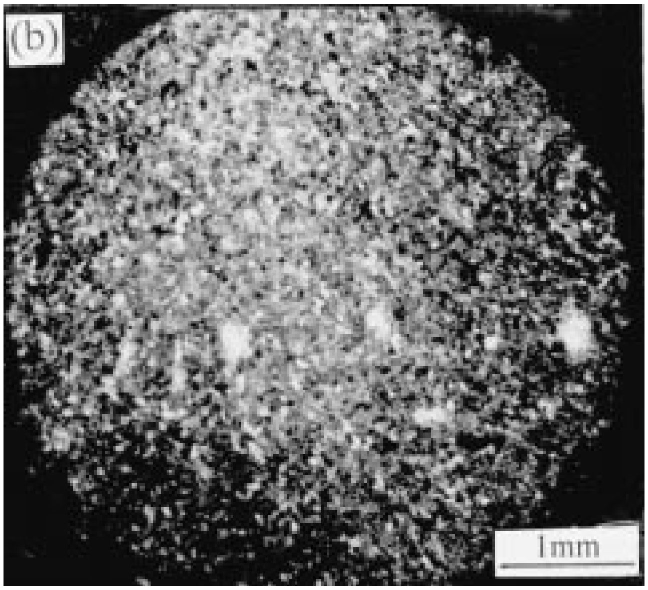


Fig. 1 Macrographic characteristics of beta flecks of Ti-10V-2Fe 3Al alloy: **(a)** macrostructure of $\alpha+\beta$-forged specimen B15, $N_f = 2.8 \cdot 10^5$; and **(b)** macrostructure of β-forged specimen C11, $N_f = 2.6 \cdot 10^5$

It seemed that beta flecks in the β-forged condition were much smaller than the $\alpha+\beta$-forged ones. There were no significant beta flecks with cross-sectional area above 0.19 mm^2 in the β-forged condition, while the maximum beta fleck in the $\alpha+\beta$-forged condition was 0.56 mm^2.

3.2 LCF Tests

The mechanical properties were given in Table 2. It could be seen that the yield strength and the ultimate tensile strength of the highly flecked specimens were higher than those were without beta flecks. The elongation, especially the reduction in area, was significantly reduced in material with beta flecks. In general, the larger the beta flecks, the higher the tensile strength and the lower the ductility.

The results of LCF tests were given in Table 3. It can be seen that beta flecks had great influence on LCF properties in spite of the data being scattered. Compared to the specimens without beta flecks, the condition with profuse beta flecks showed an inferior LCF life. The average life of the $\alpha+\beta$-forged specimens with beta flecks was 4.5×10^5. There were no significantly flecked specimens with life more than 8.7×10^5. The two unflecked specimens, however, showed a greater LCF life of about 10^7, making an order of magnitude improvement.

The examination of the fracture surfaces revealed that many cracks are present at the former β grain boundaries or subgrain boundaries in beta flecks, as shown in Fig. 3. In the highly flecked specimens, such as B15 and C12, multiple cracking that was associated with beta flecks could be observed in the fracture surfaces. It suggested that cracks tended to nucleate at grain boundaries and then grew along them. Extensive scanning electron microscopy (SEM) observation showed that beta flecks had a strong influence on nucleation and growth of LCF cracks. It could be seen in Fig. 4b that the fatigue crack of specimen 12 nucleated at one side of the fracture surface and propagated toward the other side. Chemical composition measurement at the crack initiation site showed a higher Fe content (2.92 wt.%) and a lower Al content (2.11 wt.%) than the aged beta matrix. It suggested that this origin was beta fleck. In fact, by making a comparison between an SEM fractograph (Fig. 4b) and the macrograph of the matching half (Fig. 4a), we could find that the crack initiation site had a corresponding beta fleck. In the crack propagation zones, much fatigue striation (Fig. 4c) and secondary cracking (Fig. 4d) perpendicular to the propagation direction of the main cracks could be found. It is a typical characteristic of fatigue fracture. However, some brittle zones characterized by intergranular fracture could also be found in the highly flecked specimens, as shown in Fig. 4e. Similarly, we did show that these brittle fracture zones contained higher mass fractions of Fe and lower Al content; hence, the brittle zones are beta flecks.

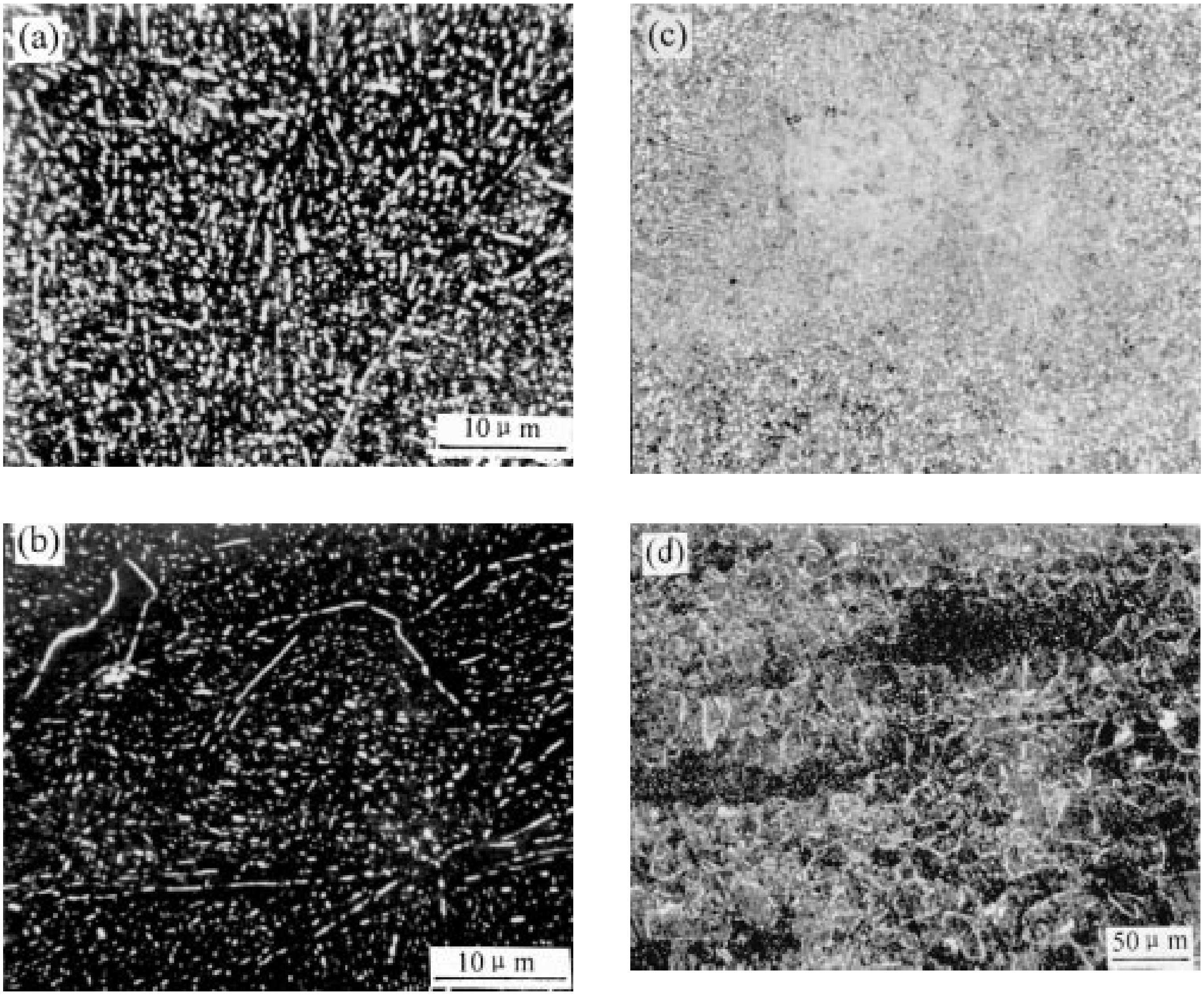


Fig. 2 Typical microstructure of specimens with or without beta flecks: **(a)** typical microstructure of $\alpha+\beta$-forged specimens without beta flecks; **(b)** typical microstructure of β-forged specimens without beta flecks; **(c)** typical microstructure of beta flecks in $\alpha+\beta$-forged specimens; and **(d)** typical microstructure of beta flecks in β-forged specimens

Table 2 The influence of beta flecks on tensile properties of Ti-10V-2Fe-3Al

Number	Ultimate tensile strength (MPa)	0.2% yield strength (MPa)	Elongation (%)	Reduction in Area (%)	Maximum β-fleck area, S_{max} (mm²)	P_A(%)(a)
B1	1335	1298	5.6	11.6	$0.52 = 1.22 \times 0.43$	13.56
B2	1336	1320	9.6	43.2	None	None
B3	1330	1298	8.0	20.8	$0.20 = 0.72 \times 0.28$	3.72
B4	1360	1310	10.4	42.0	None	None
B5	1370	1350	8.8	29.0	$0.04 = 0.30 \times 0.12$	0.20
B6	1310	1300	5.6	19.6	$0.18 = 0.46 \times 0.40$	4.25
B7	1302	1290	6.8	39.5	None	None
B8	1280	1272	8.0	20.8	$0.16 = 0.41 \times 0.38$	3.20

(a) Note: ratio of the areas of beta flecks to those of the fractured surfaces

Table 3 The influence of beta flecks on LCF properties of Ti-10V-2Fe-3Al

Number	Forging condition	Cyclic stress (MPa)	LCF life N_f (10^4)	Maximum beta-fleck area, S_{max} (mm^2)	Volume fraction of beta flecks (%)
B11	(+)	900	22	$0.34 = 0.71 \times 0.48$	4.02
B12	(+)	900	42	$0.13 = 1.05 \times 0.10$	1.33
B13	(+)	900	53	$0.14 = 0.31 \times 0.45$	1.67
B14	(+)	900	>1000	None	None
B15	(+)	800	28	$0.56 = 1.44 \times 0.39$	11.52
B16	(+)	800	87	$0.17 = 0.76 \times 0.22$	1.45
B17	(+)	800	1325	None	None
B18	(+)	800	40	$0.16 = 0.53 \times 0.11$	1.76
C11		900	26	$0.10 = 0.47 \times 0.21$	1.82
C12		900	27	$0.19 = 0.68 \times 0.28$	1.55
C13		900	48	$0.07 = 0.35 \times 0.20$	0.87
C14		900	>3104	None	None
C15		800	>258	None	None
C16		800	>943	None	None
C17		800	187	None	None
C18		800	156	None	None

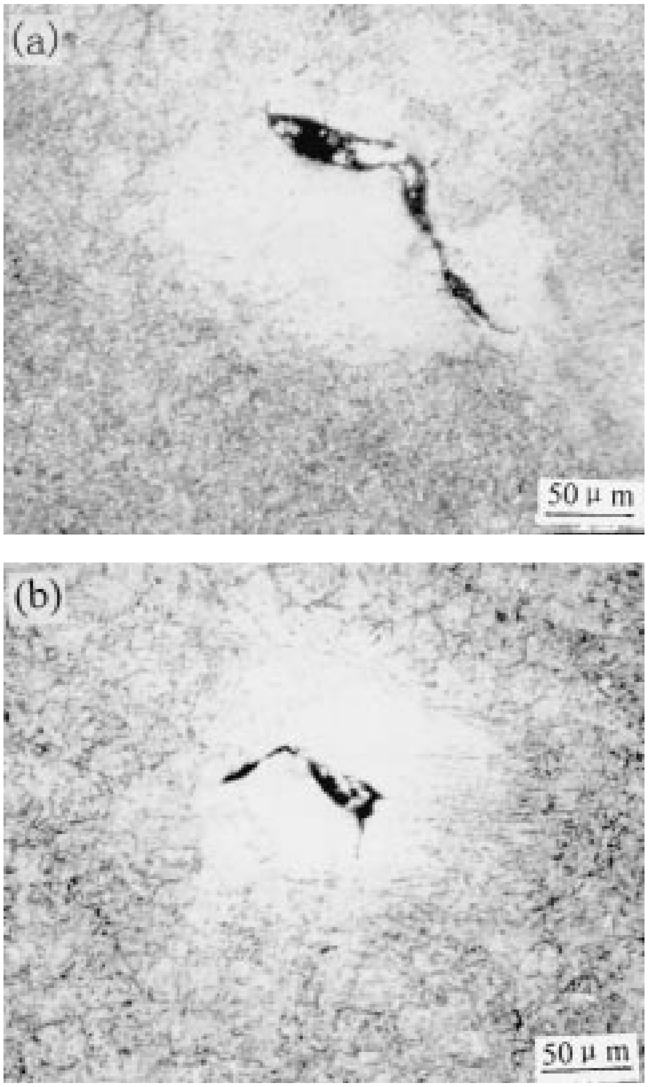


Fig. 3 Typical microstructure of $\alpha+\beta$-forged and β-forged specimens showing cracks nucleated at and propagated along beta grain boundaries:**(a)** $\alpha+\beta$-forged specimens; and **(b)** β-forged specimens

4. Discussion

Zhou *et al.* have concluded that the occurrence and severity of beta flecks could be reduced using beta forging based on extensive macrographic examinations; they attributed this improvement to a higher diffusion coefficient of Fe element in the β region.[9] A theoretical equation of the diffusion process of Fe was established based on Fick's second law under the boundary condition of $t = 0$, $x = h$, $C = C_0$.[11]

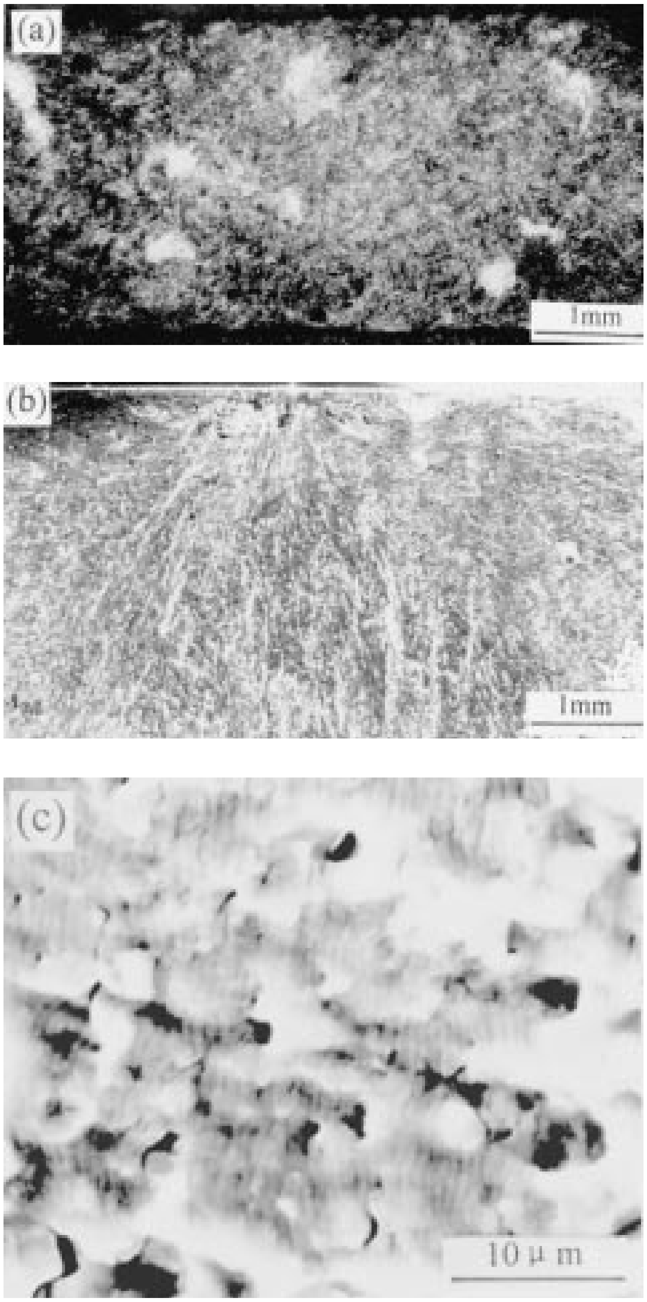
$$Cx = \frac{C_0}{2}\left[erf\ \frac{h-x}{2\sqrt{Dt}} + erf\ \frac{h+x}{2\sqrt{Dt}}\right] \qquad \text{(Eq 1)}$$

where C_x is Fe concentration at point x, C_0 is average Fe concentration of the usual aged matrix, h is half of the initial fleck thickness, x is the distance from the center of the fleck zone, D is the interdiffusion coefficient, and t is time.

The diffusion constant of Fe in β-Ti at 820 °C is $D_0 = 9.2 \times 10^{-2}\ cm^2\ s^{-1}$, $Q = 165.7KJ\ mol^{-1}$.[11] The validity of Eq 1 can be confirmed as follows. Consider, for example, β-forged specimens with a fleck thickness of 0.2 mm and an Fe concentration of 3.00 wt.%, heated at 820 °C for 1 h. The calculated value of C_x at central point is 2.99 wt.%. No obvious improvement of Fe segregation was observed as expected. It can be reasonably concluded that β forging in the 820 °C β region had no obvious improved effect on homogeneity of the segregating element Fe. The β-forged condition could mask the large size effect of beta flecks, resulting in much smaller beta flecks than $\alpha+\beta$-forged ones; it was recognized that just the chemistry difference of the fleck region might cause a significant mechanical property difference. This was in good agreement with Shamblen's conclusions.[12]

The purpose of this investigation was to find out whether beta flecks have a detrimental effect on LCF properties. The study has revealed that the highly flecked specimens showed a reduction in tensile ductility and LCF life. The larger the beta flecks, the lower the ductility and LCF life. It was noted that the relatively low LCF life was attributed to beta flecks.

It is well known that fatigue crack nucleation occurs at microscopic sites of high local plastic strain concentration.[13] For instance, slip bands, twin boundaries, grain boundaries, and inclusions are common sites of crack nucleation in various pure metal and alloys,[14,15] in Ti-10-2-3 cracks nucleated at the former grain boundaries or subgrain boundaries of beta flecks (Fig. 3). These must therefore be the sites of local plastic strain concentrations. Extensive studies have revealed that the stress or strain localization attributable to the low LCF is determined by the difference in yield stress and the strain hardening between these constituents.[16,17] The larger this difference becomes, the lower is the macroscopic strain at which crack nucleation occurs. It is well known that the aged matrix is much stronger than grain boundary due to increasing age hardening by secondary α phase, and accordingly, deformation preferentially occurs at the grain boundary (GB) α during plastic deformation. The presence of GB α film leads to long soft zones, which results in large plastic strain distributed over a relatively small zone and high stress concentration and high local strains at GB α. Therefore, cracks tend to find grain boundaries to be the nucleation sites and the path of least resistance, leading to intergranular cracking (Fig. 4e). This result is in good agreement with Terlinde's study on Ti-10V-2Fe-3Al alloy.[16,17] According to Funkenbusch's conclusion, the reduction of LCF life is most susceptible to beta flecks, which may be attributed two factors. First, the strain concentrated at grain boundaries is generally proportional to grain size and β flecks are regions of very large size. Second, grain boundaries are generally more susceptible to crack initiation at high cyclic strains. Therefore, cracks nucleate at grain boundaries and then propagate along grain boundaries, leading to premature sample failure.[6] Controlling factors for crack nucleation include the length and thickness of the soft GB α, as well as the yield stress difference between the aged matrix and the soft zone.[16,17] It can be



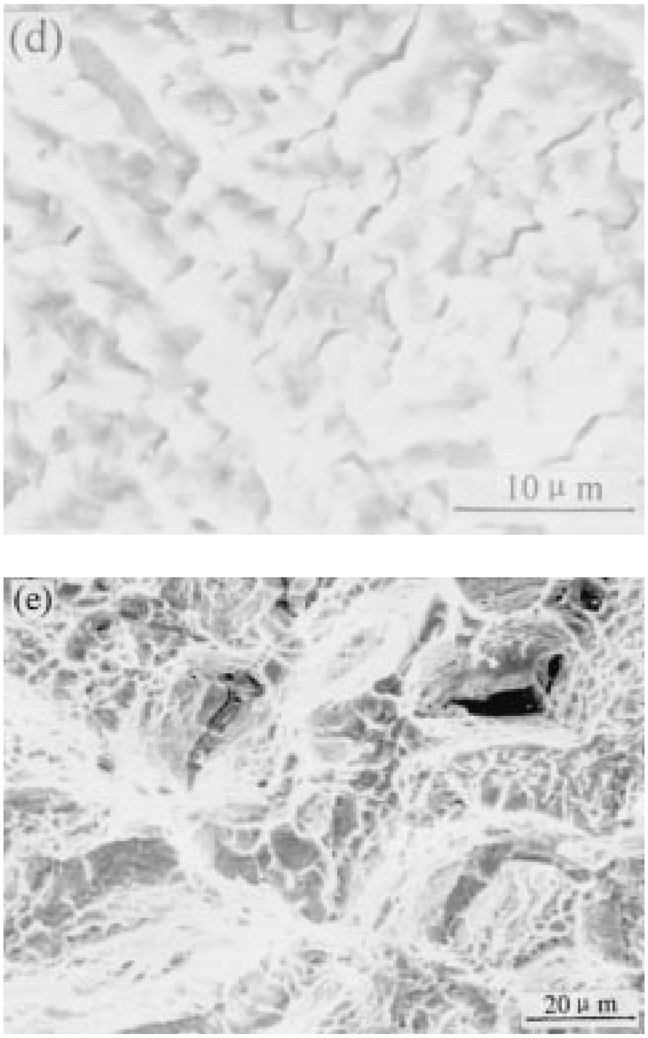


Fig. 4 Macroscopic and SEM micrograph of specimen C12: **(a)** macroscopic photograph; **(b)** macroscopic SEM photograph; **(c)** SEM micrograph showing fatigue striation in crack propagation zones; **(d)** SEM micrograph showing secondary cracks in crack propagation zones; and **(e)** SEM micrograph showing intergranular fracture in brittle fracture band

concluded that reducing the size of beta flecks by improving the melting technology or hot working technology will increase ductility and LCF life.[9]

5. Conclusions

- For both $\alpha + \beta$-processed and β-processed material, the presence of beta flecks led to a loss in LCF life and tensile ductility but an increase in strength. The larger the beta flecks, the lower the LCF life and ductility.
- Beta flecks in β-forged materials were much smaller than those of $\alpha + \beta$-forged ones. However, the LCF life and ductility of β-forged specimens were significantly reduced as those of $\alpha + \beta$ forged ones. Beta-forged materials were more susceptive to beta flecks than $\alpha + \beta$-forged ones.
- Chemical composition segregation of beta flecks could not be significantly reduced by using beta forging in the 820 °C β region for heating only 1 h. Beta forging could mask the large grain effect of beta flecks, leading to small grains.
- Beta flecks were susceptive to crack nucleation and propagation. Cracks tended to find grain boundaries to be the nucleation sites and the path of least resistance, leading to intergranular cracking. Because grain boundaries of beta flecks usually are zones of local stress or strain concentrations because of larger grains, these grain boundaries are susceptive to crack initiation at high cyclic strains.

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