HIGH CYCLE FATIGUE OF AN ORTHORHOMBIC TI-22AL-25NB INTERMETALLIC ALLOY

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Abstract

An evaluation of fatigue behavior of the orthorhombic Ti-22Al-25Nb intermetallic alloy with the duplex microstructure has been carried out with high cycle rotary bending fatigue testing at room temperature (RT), 650℃ and 750℃ with a test frequency of 50Hz. The testing results show that the fatigue strengths (σ_{-1}) are up to 530MPa at RT, 600MPa at 650℃ at or more than 1×10^{7}cycles, and 500MPa at 750℃ at 8.34×10^{6}cycles. Damage mechanisms at crack initiation sites and crack propagation were investigated with the use of scanning electron microscopy. The fatigue failure mechanisms of the duplex microstructure of the present alloy are simply discussed.

Keywords: Ordered orthorhombic Ti_2AlNb based alloy, high cycle fatigue behavior, crack initiation and propagation

Introduction

The ductility and toughness of Ti_3Al based alloys can be improved by the addition of Nb [1]. In exploring the effect of niobium on phase transformation and mechanical properties in Ti_3Al based alloys, Banetjee [2] identified a ternary intermetallic based on the stoichiometry Ti_2AlNb which was designated as the *O* phase in terms of its orthorhombic structure with Cmcm symmetry. Since then the ordered orthorhombic Ti_2AlNb based alloys have been received considerable attention because of their lower density, high yield strength and excellent high temperature performance [3]. The typical compositions of the Ti_2AlNb based alloys are Ti-22Al-23Nb and Ti-22al-27Nb etc, which showed to have higher strength but relatively low ductility and oxidation resistance [3]. Recently numerous studies have been focused on the relationship among processing, microstructure and mechanical properties of the Ti_2AlNb orthorhombic alloys [4]. It was found that the mechanical properties of Ti_2AlNb based alloys strongly depend on microstructures. CISRI has carried out a series of R & D work on Ti_2AlNb based alloys and made an extensive progress both in fundamental principle research and in application research [5,6]. A forged Ti_2AlNb based alloy with composition of Ti-22Al-25Nb (at%) has been proved to have good mechanical properties at both room and elevated temperatures especially for the duplex microstructure obtained after a solution-treatment plus an ageing treatment. Several testing components applied for aerospace and aircraft have also been successfully manufactured. The component design and life management technologies must ensure that this material can be used without operational risk. Therefore, study on fatigue behavior of this alloy is one of the important aspects for achieving the maximum useful life of the material under actual using conditions. The high cycle rotary bending fatigue tests at room temperature, 650 ^{o}C and 750 ^{o}C were carried out in order to evaluate the fatigue resistance of the alloy, and to further understand the damage mechanisms associated with the crack initiation and propagation of the alloy.

Experimental

Material used in the present study is of composition Ti-22Al-25Nb (at%). Table 1 shows the analyzed alloy chemistry, including interstitial elements. Details of the material producing and thermal-mechanical processing (TMP) are reported elsewhere [7,8]. The material was first β-forged followed by air cooling, then forged in *(α_2+B2+O)* phase field to obtain rods with about 35 mm in diameter by multiple passes. The material carried out for the fatigue testing was firstly after a solution treatment in (*O*+*B2*) phase field followed by oil quenching, and subsequently after an age treatment at a relatively lower temperature of (*O*+*B2*) field. The testing specimens were cut by spark discharge machine from the rod then fabricated with grinding machine. The gauge section of the specimens was 4mm in diameter and 52mm in length. The high cycle rotary bending fatigue tests were performed on a PUP type testing machine with a test frequency of 50Hz at RT, 650 ^{o}C and 750 ^{o}C in air respectively. Microstructure and fractographic features of the specimens were examined by scanning electron microscopy (SEM) and transmission electron microscopy (TEM).

TABLE 1. Chemical composition of the alloy

Ti (wt%)	Al (wt%)	Nb (wt%)	O (ppm)	N (ppm)
Bal.	10.82	42.12	340	54

Results and Discussions

Fig. 1 shows the SEM second electron image of the duplex microstructure (DP) that consists of fine primary *α_2/O* particles and extremely fine and crisscross lath-like *O* phase (1~2μm) distributed in the *B2* matrix without primary *B2* phase grain boundaries remained. The total volume fraction of *O* phase is about 70% in the microstructure. Fig.1 (b) further gives a micrograph of the duplex microstructure observed with TEM. The mechanical properties of the duplex microstructure of the alloy have been systematically evaluated, showing that such microstructure has good comprehensive properties both at RT and the elevated temperatures as indicated in Table 2.

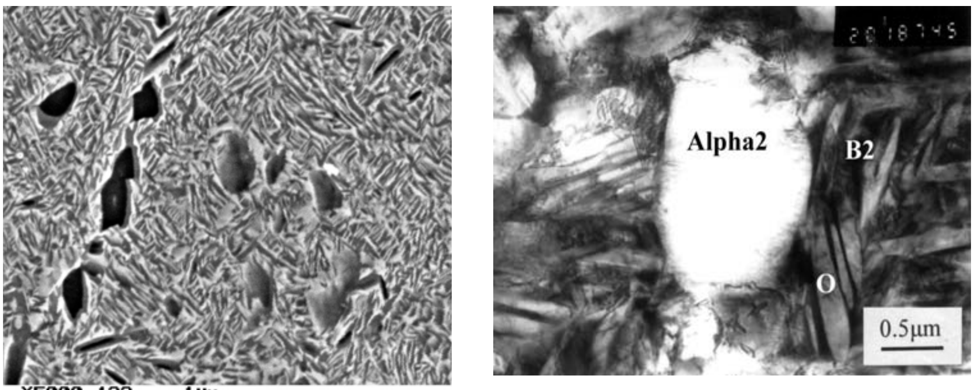
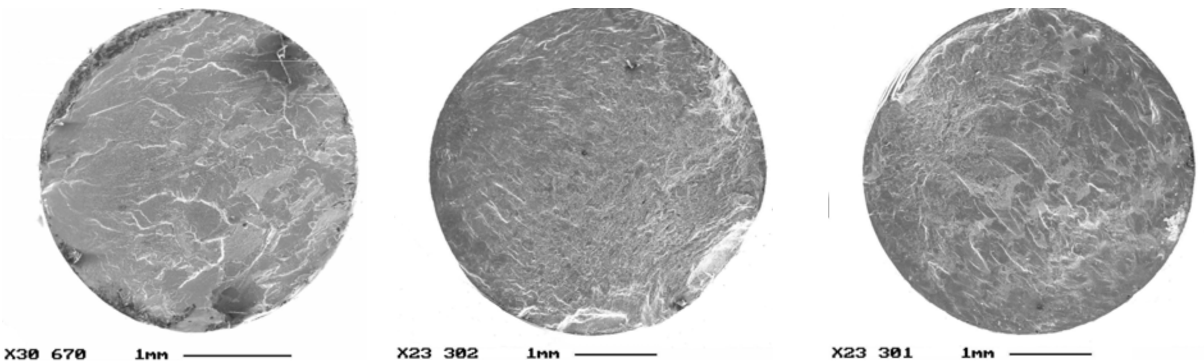


FIGURE 1. Micrographs of the duplex microstructure of Ti-22Al-25Nb alloy (a) SEM image, (b) TEM image

TABLE 2. Typical values of the tensile properties and fracture toughness of Ti-22Al-25Nb (at%) with the duplex microstructure

Temperature (℃)	σ_b (MPa)	$\sigma_{0.2}$ (MPa)	δ_5 (%)	ψ (%)	K_{Ic} (MPa.m$^{1/2}$)
22	1200	1050	9	14	30
650	950	860	13	26	/
750	750	480	13	20	/

The results of the high cycle rotary bending fatigue tests are shown in Table 3 for the duplex microstructure of the alloy at RT, 650 ^{o}C and 750 ^{o}C. The high cycle rotary bending fatigue strength (σ_{-1}) are up to 530 MPa at RT, 600MPa at 650 ^{o}C at more than 10^7 cycles, and 500 MPa at 750 ^{o}C at 8.34 $\times10^6$ cycles, which are superior to Ti_3Al based, γ-TiAl based intermetallic compound alloys and α or near α titanium alloys as well as some Ni-based superalloys such as Inco718 at the equal testing conditions. This can be attributed to the best combination of the high strength and high ductility of the duplex microstructure of the present alloy.



(a) (b) (c)

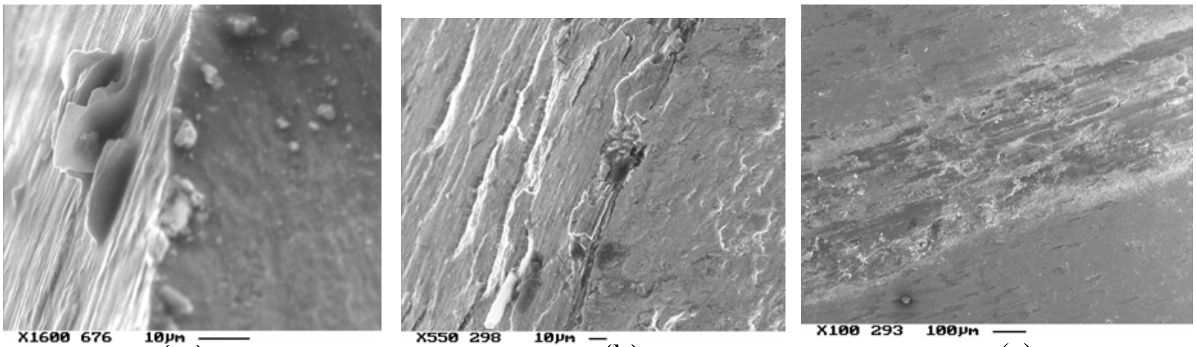
FIGURE 2. Fractographic aspects of the high cycle rotary bending fatigue fracture surface in low magnifications (a) at RT, (b) at 650 ^{o}C and (c)at 750 ^{o}C

TABLE 3. High cycle rotary bending fatigue test data for Ti-22Al-25Nb(at%) alloy with the duplex microstructure at RT, 650 ^{o}C and 750 ^{o}C.

Specimen Code	Test Temperature	Stress amplitude σ_{-1}(MPa)	cycles to be broken
1	RT	706	2.58x10^4
2		608	3.89x10^4
3		569	5.08x10^4
4		569	7.32x10^4
5		549	2.02x10^6
6		549	>1.10x10^7
7		530	>1.29x10^7
8		530	>1.00x10^7
9		620	1.00x10^6
10		620	1.98x10^6

11		620	5.68×10^{6}
12	650 °C	600	$>1.02 \times 10^{7}$
13		600	$>1.05 \times 10^{7}$
14		580	$>1.17 \times 10^{7}$
15		500	$>1.21 \times 10^{7}$
16		560	5.75×10^{6}
17		540	3.78×10^{6}
18	750 °C	520	3.65×10^{6}
19		500	8.34×10^{6}

The typical fatigue fracture morphology at low magnifications for the present material condition are shown in Fig.2 (a), (b) and (c). On a macro-scale, relatively smooth fracture surfaces were observed for the all specimens tested. The relatively smaller ratios of the fatigue regions obtained on the fracture surfaces for the specimens tested at RT imply that the fraction of the total fatigue life of the material resulting from crack propagation at RT is small (about 1/4). However, about one half and more than one half ratios of the fatigue regions were observed on the fracture surfaces of the specimens tested at 650°C and 750°C respectively, indicating that the fractions of the total fatigue life resulting from fatigue crack growth in the elevated temperature cases are larger. It was also found that on a macroscopic scale, little difference in fracture surface morphology was recognized between the fatigue tests performed at RT and the elevated temperatures, but a blue color film covered on the fracture surfaces of the specimens tested both at 650 °C and 750 °C, revealing that oxidation possibly is one of the factors which attributed to the environmental effects.



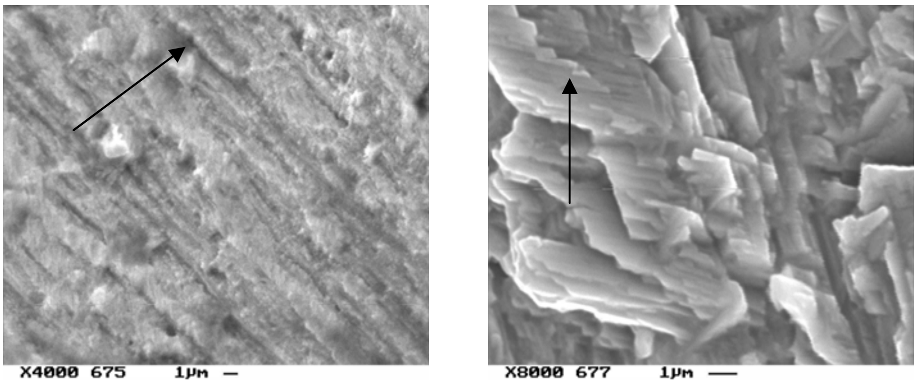
(a) (b) (c)

FIGURE 3.Extrusion and intrusion characteristics observed on the specimen surfaces near the crack initiation sites (a) at RT, (b) at 650℃ and (c) an unbroken specimen tested at 650℃ after 1.17×10^{7}cycles

All initiation sites of the duplex microstructure were located at the surface of the specimens. Some extrusion and intrusion characteristics appeared to be recognizable on the specimen surfaces either for the specimens tested at RT or at the elevated temperatures. Fig. 3(a) shows some extrusions occurred on the specimen surface near the fatigue crack initiation site where the intrusions can also be recognized which promote the crack nucleation. More pronounced extrusion and intrusion features were observed for the specimens tested at 650 °C and 750 °C as shown in Fig.3(b). Observation on an unbroken specimen surface fatigued at 650 °C after 1.17×10^{7} cycles found the extrusions and intrusions to be localized in an about 400 μm of narrow region which encircle the specimen surface as shown in Fig.3(c). These features can be related to more slip involved at the high temperatures during the reverse fatigue as well as the oxidation effect. The occurrence of the extrusions and intrusions on the surfaces of the specimens suggests that as in metallic materials, the intrinsic fatigue-crack initiation and growth for the orthorhombic phase based intermetallic alloy may also be associated with the localized plastic deformation occurred on the specimen surface and the accumulation of irreversible strain at the crack tip through dislocation substructure development.

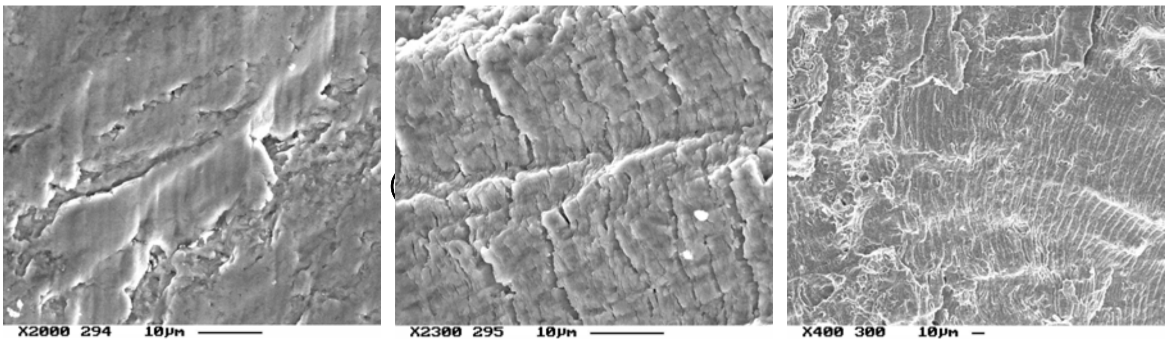
Fractographic examination on the fatigue crack growth regions showed that predominant translamellar cracking occurred for the tests at RT as shown in Fig. 4(a) and (b). On a finer scale, small step-like patterns were observed on the individual randomly oriented translamellar fracture facets shown in Fig. 4(b), which appears to be related to the duplex microstructure containing the extremely fine and crisscross lath-like *O* phase distributed in the *B2* matrix. The crack reinitiated at the step-like patterns can be seen clearly in Fig .4(b), indicating a discontinuous propagating in nature.

Examination of the fracture surfaces of 650 ^{o}C and 750 ^{o}C fatigue cracking revealed a predominant mode of fracture associated with striation markings as shown in Fig.5 (a), (b) and (c). More ductile striations markings were much often observed at the crack growth regions far from the crack initiation sites, indicating less localized plastic deformation involved in these areas during fatigue cracking. More secondary cracks were observed for the specimen tested at 650 ^{o}C to occur along the striation marking particularly at the areas far from the crack initiation site, which generally may retard the macroscopic crack growth rate. The interspaces of the striations are quit larger for the fatigue cracking occurred at 750 ^{o}C than that at 650 ^{o}C. The different of the interspace of the striations presented at the different testing temperatures indicates the different crack growth rates occurred. This feature is consistent with the high cycle rotary bending fatigue testing data as shown in Table 3. Therefore the temperature effects on crack growth are significant for the present alloy. This behavior can be interpreted in terms of the competing effects of



(a) (b)

FIGURE 4. Fractographic features of the translamellar cracking observed for the specimen tested at RT, (a) near the crack initiation site (b) at the crack growth region about 1 mm far from the crack initiation site. The arrows indicate that the rack propagation direction



(a) (b) (c)

FIGURE 5. Fractographic aspects of the striation markings (a) at 650 ^{o}C, near the cracking initiation site, (b) at 650 ^{o}C, 1.5 mm far from the crack initiation site and (c) at 750 ^{o}C, 2.5mm far from the crack initiation site

increasing intrinsic ductility and environmentally induced degradation with increasing temperature [9,10]. This hypothesis is also supported by the investigation of oxidation-resistance of the present alloy in our recent work, which showed that the oxidation –resistance of Ti-22Al–25Nb alloy is quit better at 650 ^{o}C than at 750 ^{o}C.

Summary

The present study on high cycle rotary bending fatigue cracking behavior of Ti-22Al-25Nb (at%) alloy with the duplex microstructure revealed the following:

1. The duplex microstructure of the present alloy exhibits very good high cycles fatigue cracking resistance both at room and the elevated temperatures
2. Extrusion and intrusion features were observed on the all examined specimen surfaces to promote crack nucleation. More pronounced extrusion and intrusion features were observed for the specimens tested at 650 ^{o}C and 750 ^{o}C.
3. Predominant translamellar cracking occurred for the tests at RT. On a finer scale, small step-like patterns were observed on the individual randomly oriented translamellar facets, which appear to be attributed to the effect of the duplex microstructure characteristics.
4. Predominant mode of fracture associated with striation markings occurred for the tests at 650 ^{o}C and 750 ^{o}C, and more ductile striations with larger interspaces were much often observed for the specimens tested at 750^{o}C, which may be interpreted in terms of competing of increasing intrinsic ductility and environmentally induced degradation with increasing temperature.

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