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Influence of heat treatment on microstructure and damage tolerance property in Ti-6Al-2Zr-1Mo-1V

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Abstract: The influence of heat treatment on the microstructure and damage tolerance property of Ti-6Al-2Zr-1Mo-1V titanium alloy was investigated. The large-thickness Ti-6Al-2Zr-1Mo-1V titanium alloy plate was produced by β-processing, following with duplex anneal in (α+β) phase field and β anneal, respectively. The fatigue crack propagation rate(da/dN) test and the fracture toughness(K_{1C}) test of Ti-6Al-2Zr-1Mo-1V were performed. The results show that the annealing in (α+β) phase field, with increasing anneal temperature, prior β grain size and α colony size of Ti-6Al-2Zr-1Mo-1V remained constant approximately, α lamella mean size increases gradually; K_{1C} increases and da/dN decreases respectively; when annealing in β phase field, prior β grain size and α colony size increases sharply, da/dN decreases drastically. β anneal is better than anneal in (α+β) phase field as to improve the damage tolerance property of Ti-6Al-2Zr-1Mo-1V.

Key words: Ti-6Al-2Zr-1Mo-1V ; microstructure ; crack propagation rate; fracture toughness

1 Introduction

The study of damage tolerance property(fracture toughness and fatigue crack growth rate) in titanium alloys has received considerable interest[1−6] because of their important use in aerospace applications due to their high specific strength (strength/density).The damage tolerance property of titanium alloys, however, is complicated by the changes in the microstructures that occur by even small changes in heat treatment that in turn result in changes in their properties. It has been proved that β working(deformation or annealing in β phase field) and reducing the content of interstitial elements(C,N,O, etc) can improve damage tolerance property of titanium alloys[7].

It has been known that Ti-6Al-2Zr-1Mo-1V exhibits good comprehensive mechanical property, workability and weldability. In this paper, the content of oxygen, carbon and nitrogen of Ti-6Al-2Zr-1Mo-1V were reduced to extra-low inerstitial(ELI) grade, and the microstructure characteristic parameters and damage tolerance property of Ti-6Al-2Zr-1Mo-1V, in different heat treatment conditions(including β annealing), were examined. The interrelationships of heat treatments, microstructures and damage tolerance property were discussed. And the comparison of damage tolerance property between Ti-6Al-2Zr-1Mo-1V and Ti-6Al-4V ELI had also been performed.

2 Experimental

The Ti-6Al-2Zr-1Mo-1V plate was received in such hot working history as: three vacuum arc meltings to obtain the billet of 720 mm in diameter, forging to plate of 300 mm thickness, and first rolling at 1 050 ℃ ($\varepsilon \approx$ 75%, in β phase field),then second rolling at 950 ℃ ($\varepsilon \approx$ 60%, in (α+β) phase field), at last obtaining the plate with the dimension of 80 mm×2 000 mm×L mm.

The β transformation point T_β of Ti-6Al-2Zr-1Mo-1V was 970 ℃ measuring by metallographic method. The chemical composition of Ti-6Al-2Zr-1Mo-1 V used for this study was shown in Table 1.

In order to study the influence of heat treatment on microstructure and damage tolerance property of Ti-6Al-2Zr-1Mo-1V, annealing in β phase field and

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Table 1 Chemical composition of Ti-6Al-2Zr-1Mo-1V (mass fraction, %)

Al	Mo	V	Zr	Fe	O
6.2	1.7	2.0	2.0	0.04	0.07
C	N	Si	H	Ti	
0.02	0.02	0.03	0.012	Bal.	

double anneal in $\alpha+\beta$ phase field were performed respectively. The different heat treatments were listed in Table 2.

Table 2 Heat treatments of Ti-6Al-2Zr-1Mo-1V plate

No.	Heat treatment	Abbreviation
1	910 ℃, 1 h AC + 700 ℃, 8 h FC	A1
2	930 ℃, 1 h AC + 700 ℃, 8 h FC	A2
3	950 ℃, 1 h AC + 700 ℃, 8 h FC	A3
4	980 ℃, 1 h AC + 700 ℃, 8 h FC	A4

For double anneal in $\alpha+\beta$ phase field in this paper, secondary anneal was set at 700 ℃, 8 h FC constantly. And secondary anneal had little effect on the mechanical property of Ti-6Al-2Zr-1Mo-1V plate actually[8−11]. In this study , the interrelationship of heat treatment, microstructure and damage tolerance property were investigated primarily.

After heat treatment, the samples were taken from each plate, the microstructure characteristic parameters were measured by the Secant Method. Then, the room temperature tensile tests were conducted on AG-501CNE stretch test machine, fracture toughness tests were conducted on MTS-810-500KN test machine, fatigue crack growth rate tests were conducted on MTS-810-25KN test machine respectively.

3 Results and discussion

3.1 Microstructure

The microstructure of Ti-6Al-2Zr-1Mo-1V plate in the as-received condition was shown in Fig.1. The microstructure of Ti-6Al-2Zr-1Mo-1V samples after different heat treatments were shown in Fig.2.

The microstructure of Ti-6Al-2Zr-1Mo-1V plate in the as-received condition is typical lamella microstructure, containing a discontinuous prior β boundary (Fig.1). Because anneal in ($\alpha+\beta$) phase field had little effect on the type of microstructure of ($\alpha+\beta$) titanium alloy, the microstructures of anneal in ($\alpha+\beta$) phase field (Fig.2(a), Fig.2(b), Fig.2(c)) are similar to that in the as-received condition(Fig.1). The microstructure in β anneal condition(Fig.2(d)) is typical acicular widmanstatten structure, which containing a

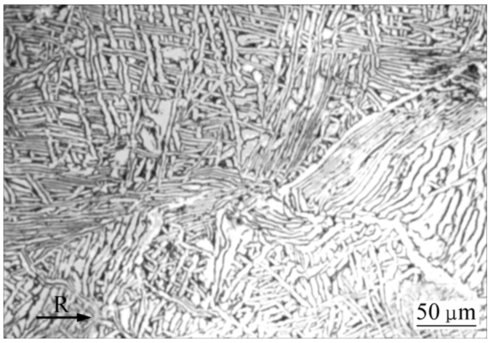

Fig.1 Microstructure of Ti-6Al-2Zr-1Mo-1V plate in as-received condition (T-R direction, R: rolling)

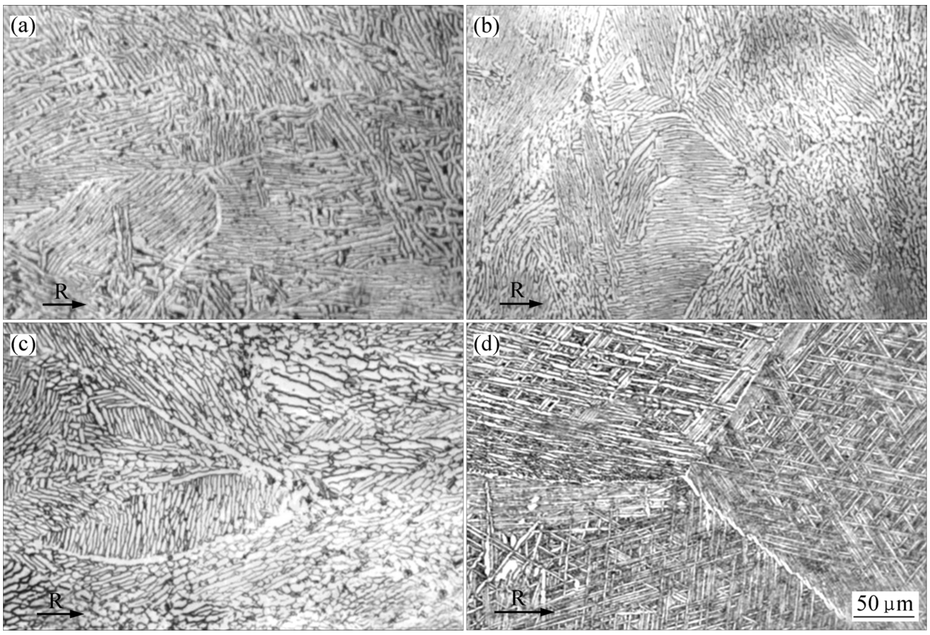

Fig.2 Microstructures of Ti-6Al-2Zr-1Mo-1V after different heat treatments (T-R direction): (a) A1; (b) A2; (c) A3; (d) A4

continuous prior β boundary and acicular α lamella aligned disorderly.

3.2 Tensile properties

The tensile property of Ti-6Al-2Zr-1Mo-1V plate in different heat treatment conditions was shown in Table3. It can be observed from Table1 that annealing in (α+β) phase field, with anneal temperature increasing, both strength (σ_m, $\sigma_{p0.2}$) and plasticity(δ_5, δ) decreased; and annealing at 10 ℃ above β transition point, strength property of Ti-6Al-2Zr-1Mo-1V was higher than that annealing in (α+β) phase field apparently, the tensile strength (σ_m) reached to 975 MPa; but plasticity decreased drastically , comparing with that annealing in (α+β) phase field.

Table 3 Influence of heat treatments on tensile behaviour of Ti-6Al-2Zr-1Mo-1V(RT)

Heat treatment	σ_m/MPa	$\sigma_{p0.2}$/MPa	δ_5/%	δ/%
A1	915	880	16	39
A2	895	860	14	33
A3	881	845	12	25
A4	975	890	8	14

3.3 Fracture toughness and fatigue crack growth rate

In different heat treatment conditions, the micro-structure characteristic parameters (Prior β grain size(D), α colony size(d), α lamella mean size(b) and fracture toughness were shown in Table 4. It can be observed from Table 4 that while annealing in (α+β) phase field, with anneal temperature increasing, prior β grain size and α colony size of Ti-6Al-2Zr-1Mo-1V remained constant approximately, but α lamella mean size increased gradually, and fracture toughness also increased in certain degree. It can be illustrated that the increasing of α lamella mean size was a beneficial factor for improving the fracture toughness of Ti-6Al-2Zr-1 Mo-1V [12−15]; while annealing at 10 ℃ above β transition point, prior β grain size and α colony size of Ti-6Al-2Zr-1Mo-1V increased sharply, K_{1C} reached to 116.45 MPa·m$^{1/2}$, which was equivalent to that annealing at 950 ℃, the upper temperature in (α+β) phase field.

Table 4 Influence of heat treatments on microstructure and K_{1C} of Ti-6Al-2Zr-1Mo-1V

Heat treatment	D/μm	d/μm	b/μm	K_{1C} /(MPa·m$^{1/2}$) (T-L direction)
A1	308	110	3.12	85.60
A2	314	108	3.65	100.05
A3	312	115	4.64	114.30
A4	617	251	1.66	116.45

Fatigue crack growth rate(da/dN) curves of Ti-6Al-2Zr-1Mo-1V in different heat treatment conditions, at room temperature and under the atmosphere condition, were shown in Fig.3. When annealing in (α+β) phase field, with anneal temperature increasing, α lamella mean size increased gradually, and fatigue crack growth rate da/dN decreased gradually. When annealing at 10 ℃ above β transition point, fatigue crack growth rate da/dN decreased drastically comparing with that annealing in (α+β) phase field. Thus, it can be proved that β anneal was favorable to improve the damage tolerance property of Ti-6Al-2Zr-1Mo-1V compared with (α+β) phase field anneal[16−20], and increasing annealing temperature in (α+β) phase field would also benefit the damage tolerance property of Ti-6Al-2Zr-1Mo-1V [21−23].

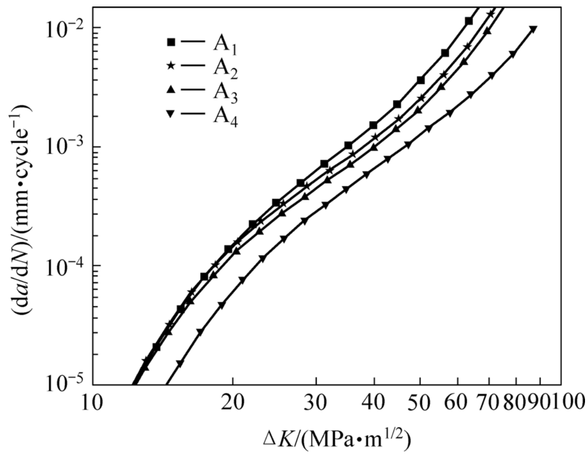

Fig.3 Influence of heat treatment on fatigue crack growth rate of Ti-6Al-2Zr-1Mo-1V (R=0.1, RT, AT)

3.4 Ti-6Al-2Zr-1Mo-1V and Ti-6Al-4VELI

In 1981, US issued aerospace material specification-AMS4905A-titanium alloy, damage-tolerance grade plate 6Al-4V beta annealed, which the latest version is AMS4905C, issued in 2004. This specification defined many technology requirements, including the chemical composition range, heat treatments, basic mechanical property requirements and so on. The tensile properties of Ti-6Al-4VELI and Ti-6Al-2Zr-1Mo-1V plate were shown in Table 5 and Table 6 respectively.

Comparing the comprehensive property of Ti-6Al-2Zr-1Mo-1V and Ti-6Al-4VELI, it can be observed from Table 5 and Table 6, when annealing at 10 ℃ above β transition point, the strength(σ_m and $\sigma_{p0.2}$)and fracture

Table 5 Tensile properties of Ti-6Al-4VELI plate specified in AMS4905C

Plate thickness/ mm	σ_m/ MPa	$\sigma_{p0.2}$/ MPa	δ_5/ %	K_{1C}(K_Q)/ (MPa·m$^{1/2}$) (T-L)
50.80−101.60	≥841	≥745	≥8	≥93

Table 6 Tensile properties of Ti-6Al-2Zr-1Mo-1V plate

Hot treatment	σ_m/ MPa	$\sigma_{p0.2}$/ MPa	δ_5/ %	δ/ %	K_{IC}/ (MPa·m$^{1/2}$) (T-L)
A2	895	860	14	33	100.05
A3	881	845	12	25	114.30
A4	975	890	8	14	116.45

toughness (K_{IC}) of Ti-6Al-2Zr-1Mo-1V were obviously better than that of Ti-6Al-4VELI defined in AMS4905C; when annealing at 930 ℃ and 950 ℃, the upper temperature in (α+β) phase field, the strength and fracture toughness of Ti-6Al-2Zr-1Mo-1V were equivalent to which of Ti-6Al-4VELI defined in AMS4905C.

4 Conclusions

1) Ti-6Al-2Zr-1Mo-1V annealing in (α+β) phase field, with anneal temperature increasing, prior β grain size and α colony size remained constant approximately, α lamella mean size increased gradually; K_{IC} increased and da/dN decreased respectively. Increasing of α lamella mean size was beneficial to improve damage tolerance property of Ti-6Al-2Zr-1Mo-1V.

2) Ti-6Al-2Zr-1Mo-1V annealing at 10 ℃ above β transition point, the microstructure was transformed into acicular widmanstatten structure, prior β grain size and α colony size increased sharply, da/dN decreased drastically. β anneal was better than (α+β) phase field anneal for damage tolerance property of Ti-6Al-2Zr-1Mo-1V.

3) Annealing in β phase field, the damage tolerance (K_{IC}, da/dN) of Ti-6Al-2Zr-1Mo-1V was obviously better than that of Ti-6Al-4VELI defined in AMS4905C.

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