Microstructure and Mechanical Properties in Weld Heat Affected Zone of Titanium Alloy†

Toshio ENJO*, Toshio KURODA and Masashi NISHIZAWA*****

Abstract

Microstructure of weld heat affected zone of Ti-6Al-4V alloy was investigated by means of transmission electron microscopy and relation between microstructure and mechanical property, fracture toughness and delayed cracking characteristics were discussed.

The mill annealed specimen and the specimen heat-treated at 973 K were consisting of $\alpha + \beta$ microstructures. The β phase increased with increasing heat treatment temperature. However, the mechanical property and fracture toughness were hardly changed. The crack growth rate in water increased with increasing heat treatment temperature.

For the specimen heat-treated at 1073 K to 1223 K, the microstructure was $\alpha + \alpha'$ microstructure, α' phase increased with increasing heat treatment temperature. K_{IC} increased from 40 MPa$\sqrt{m}$ to 67 MPa$\sqrt{m}$ with increasing heat treatment temperature. The crack growth rate in water of delayed cracking decreased with increasing heat treatment temperature. For the specimen heat-treated at 1273 K to 1473 K, the microstructure was α' phase. The tensile strengths in both specimen were 1100 MPa to 1200 MPa and is higher than that of the mill annealed specimen. The crack growth rate of the delayed cracking in water was very slow, because of the α' microstructure.

KEY WORDS : (Ti-6Al-4V Alloy) (Microstructure) (Welds) (Fracture Toughness) (Transmission Electron Microscopy)

1. Introduction

Titanium alloy such as Ti-6Al-4V has been widely used for various structures in aerospace industries. This alloy can be numerous microstructures by means of heat treatment and welding process[1)-3)]. It is well known that the microstructure change occurs in the weld heat affected zone. But the microstructure has not been clearly yet, because of the limit of analysis by means of light microscopy. The shape and distribution of the β phase, α phase and α' phase is considered to affect the mechanical properties, fracture toughness and hydrogen induced cracking.

In this paper, the microstructure of the weld heat affected zone of Ti-6Al-4V alloy has investigated in details by means of transmission electron microscopy, and the role of the microstructure on the mechanical properties was investigated.

2. Experimental Procedures

Ti-6Al-4V alloy plate was received in a mill annealed state. The thickness was 20 mm. The chemical compositions are shown in **Table 1.** The microstructure was made by heat treatment. The heat treatments were performed in a vacuum furnace. The specimens were heated at 923 K to 1473 K for 7.2 ks and then water-quenched. The microstructure of the treatment is corresponded to that of the heat affected zone for electron beam welding with rapid cooling rate.

The microstructure was studied using transmission electron microscopy. The specimens for transmission electron microscopy were prepared by jet polishing in electrolyte consisting of perchrolic acid, butylalcohl and methanol at 14.5 V and below 233 K. The volume fractions of the β phase, α phase and α' phase were evaluated by X-ray diffraction technique using Cu radiation filtered by Ni.

Table 1 Chemical compositions of Ti-6Al-4V alloy (mass%).

Al	V	C	Fe	N	O	H	Ti
6.26	4.15	0.011	0.204	0.0042	0.146	0.0045	Bal

For the mechanical properties, the smooth bar specimen in the gage diameter of 4 mm was used. The tensile test was carried out at a crosshead speed of 1.7×10^{-2}

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mm/s using Instron type tensile machine.

The fracture toughness K_{IC} was evaluated by three point bending test. The test specimen dimension and test condition was made on the basis of ASTM E399. The delayed cracking test was carried out using cantilever beam type apparatus. The crack growth rate was measured.

3. Results and Discussion

3.1 Relation between heat treatment temperature and microstructure

Figure 1 shows microstructures of the mill annealed specimen and the specimen heat-treated at 973 K to 1473 K. The mill annealed specimen is consisting of $\alpha + \beta$ microstructure. α phase is observed as white platelets, and β phase is observed as dark lines at α/α interface as shown

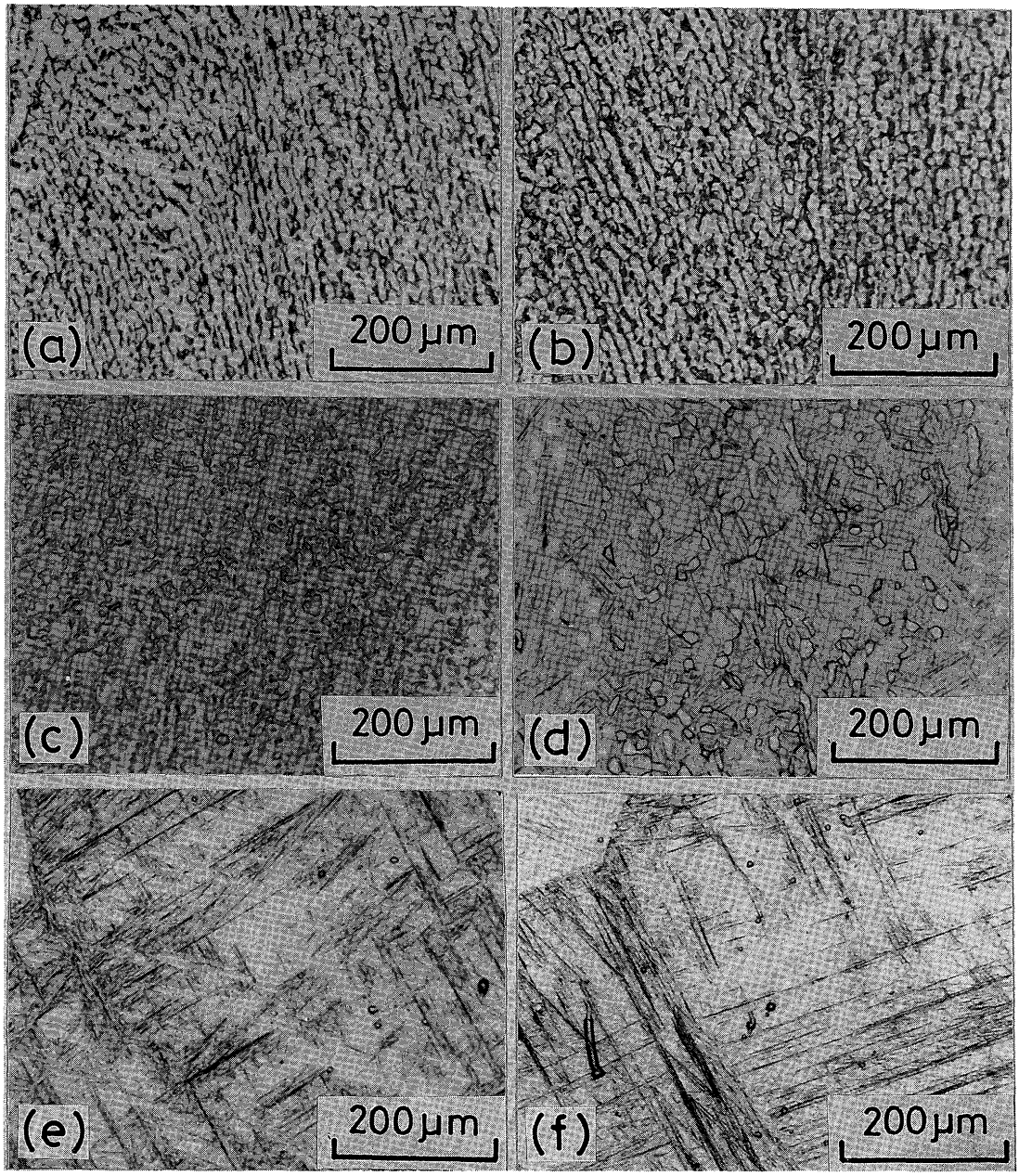

Fig. 1 Optical micrographs of the specimen heat-treated at various temperatures for 3.6 ks respectively. (a) mill annealed. (b) Treated at 973 K. (c) Treated at 1073 K, (d) Treated at 1223 K. (e) Treated at 1273 K. (f) Treated at 1473 K.

in Fig.1-(a). The microstructure is consisting of a continuous, exuiaxed α phase with a fine, continuous β phase at the α grain boundary. The specimen at 973 K is also consisting of $\alpha + \beta$ microstructure, which is as same as that of the mill annealed specimen.

For the specimen heat-treated at 1073 K as shown in Fig.1-(c), primary α phase is observed as white regions and β phase is observed as the dark colonies. But the appearance of the microstructure is different from that of the mill annealed specimen.

For the specimen heat-treated at 1223 K as shown in Fig.1-(d), the microstructure is consisting of primary α phase of the block type and α' phase. The volume fraction of the α' phase is high, and the matrix becomes α' phase. α'phase generates from the β phase by rapid cooling from the heat treatment temperature.

For the specimen heat-treated at 1273 K and 1473 K as shown in Fig.1-(e) and (f), the microstructures are consinsting of α' phase. The microstructure is all α' phase above 1273 K, and α' phase generates by quench treatment from the temperature.

Then, the microstructure was observed in detall by transmission electron microscopy.

Figure 2 indicates transmission electron micrographs of the mill annealed specimen(a) and the specimen(b) heat-treated at 973 K. The microstructures in both specimen are consisting of α phase and β phase. The β phase is present between α phases.

For the specimen heat-treated at 973 K, the width of the β phase is larger than that of the mill annealed specimen. The martensite transformation hardly occurs at the heat-treatment.

Figure 3 indicates transmission electron micrographs of the specimen heat-treated at 1073 K and 1223 K. The microstructure in both specimen is consisting of primary α phase and α' phase. As shown in **Fig.3-(a),** α' phase is present at the region between primary α phase. This phase is hardly observed for the specimen heat-treated at 973 K as shown in Fig.2-(b).

Dislocation density in the α phase is high by the α' transformation. Consequently, the microstructure is consisting of $\alpha + \alpha'$ phase at the heat treatment temperature, and α' phase generates from the β phase by quenching.

For the specimen heat-treated at 1223 K, the microstructure is consisting of primary α phase and α' phase , the volume fraction of the α' phase becomes larger. β phase is hardly observed.

Figure 4 indicates transmission electron micrographs of the specimen heat-treated at 1273 K and 1473 K. The microstructure is consisting of α' phase. The α' phase generates by the quench treatment from above the β transus temperature. The lath width and length of the α' phase at 1473 K are larger than that of the specimen at 1273 K.

Figure 5 indicates X-ray line profiles of the mill annealed specimen. The diffraction peak of the α' phase is observed as well as the peak of β phase. Then the volume fraction of the β β phase was evaluated.

Figure 6 indicates the relation between volume fraction of the β phase and heat treatment temperature.

The volume fraction of the β phase increased with increasing heat treatment temperature up to 1073 K. But the volume fraction of the β phase is very small above 1073 K.

Generally. the volume fraction of the β phase increases with increasing heat treatment temperature. But the β phase transforms α' martensite phase during quench from the temperature above 1073 K. α' martensite phase is hcp structure and the difference between diffraction angle of the α phase peak and that of α' phase peak could not be distinguished.

When the alloy was solution-treated above the β

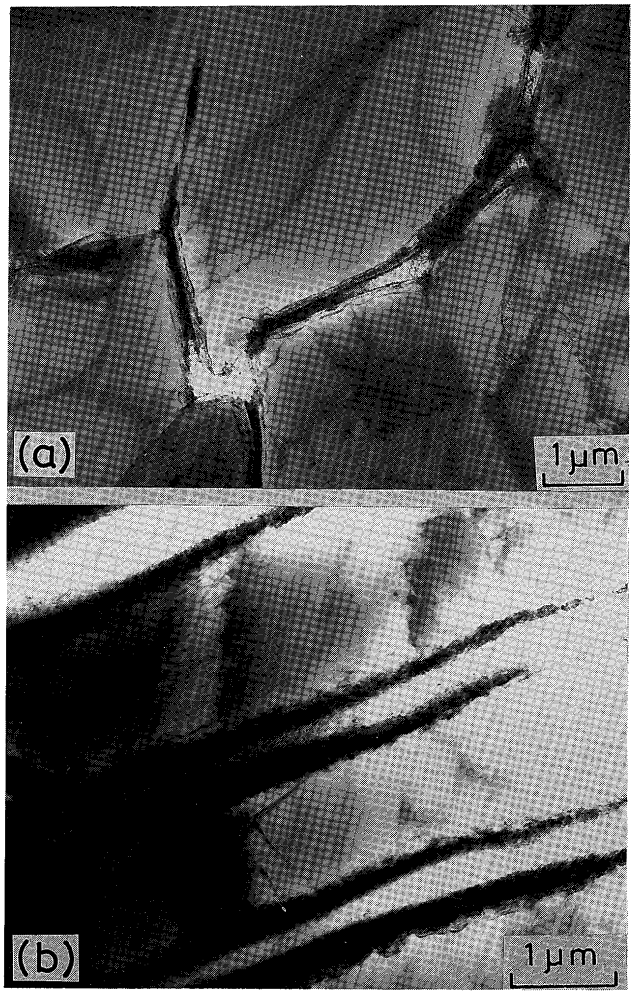

Fig. 2 Transmission electron micrographs of mill annealed specimen (a) and the specimen heat-treated at 973 K (b).

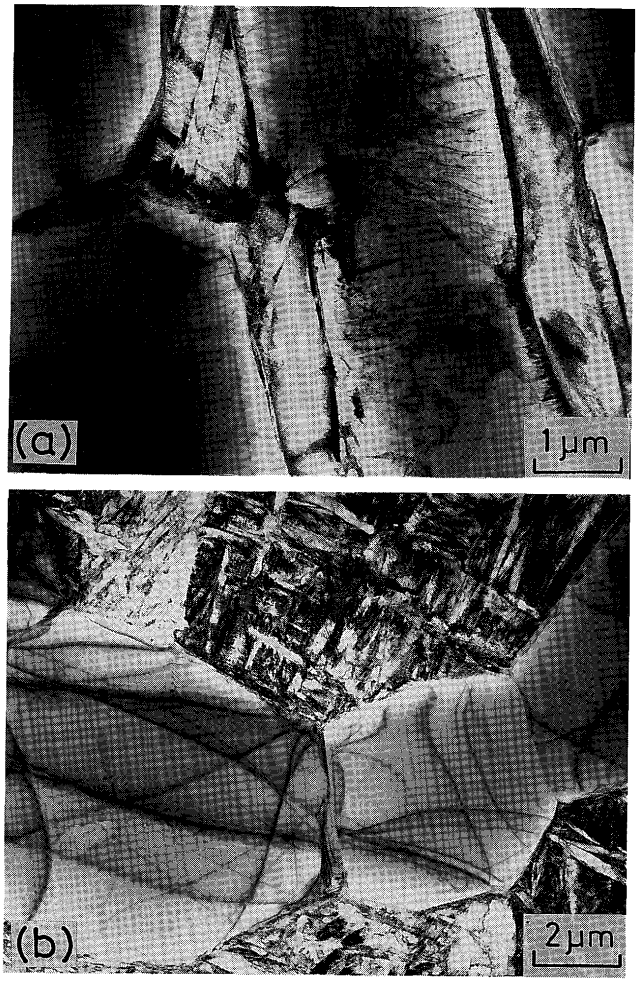

Fig. 3 Transmission electron micrographs of the specimens heat-treated at 1073 K (a) and 1223 K (b).

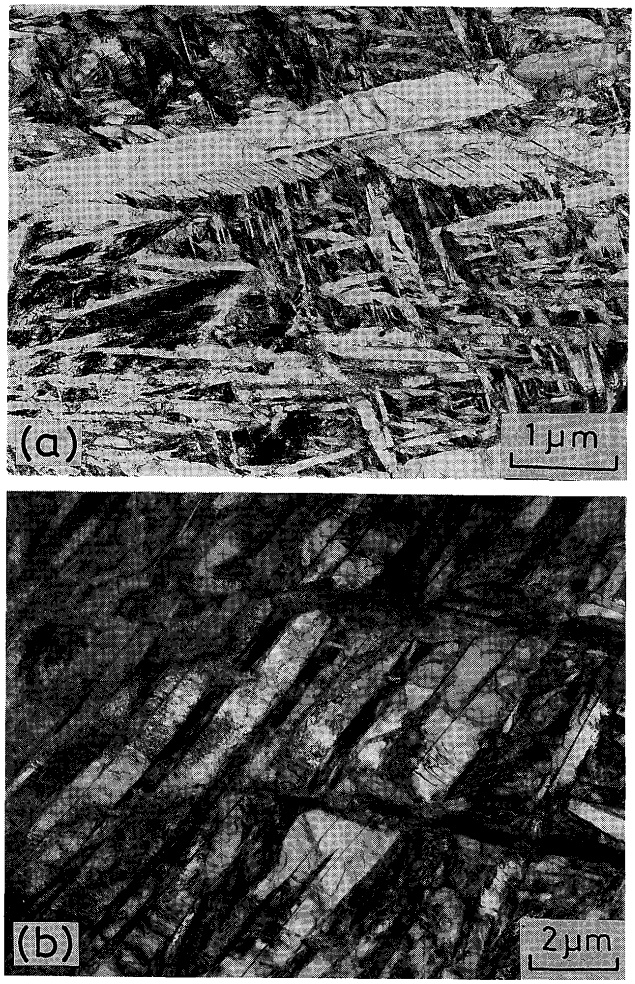

Fig. 4 Transmission electron micrographs of the specimens heat-treated at 1273 K (a) and 1473 K (b).

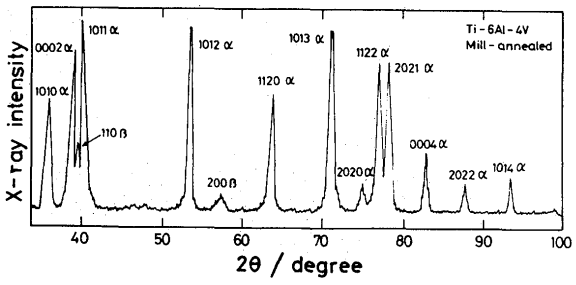

Fig. 5 X-ray diffraction pattern of mill annealed specimen.

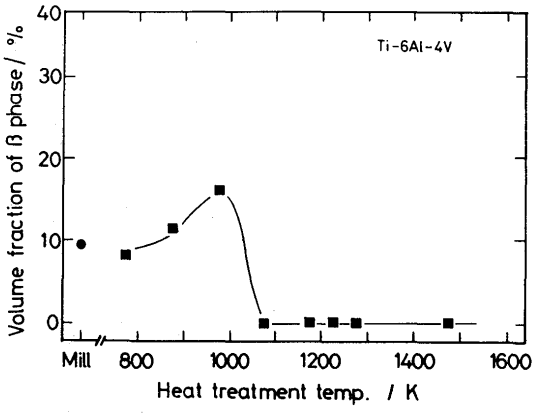

Fig. 6 Relation between volume fraction of β phase and heat treatment temperature.

transus temperature at 1273 K, the aluminium and vanadium in the Ti-6Al-4V alloy are uniformly distributed throughout the β phase. Because this is a lean β alloy, the β phase becomes unstable during the water quench, and β to α' martensite transformation results.

At heat treatment temperature below the β transus temperature such as the heat treatment temperature at 1073 K and 1223 K, which both α and β phasses exist in equilibrium.

The α phase that forms rejects the β stabilizing element(V). The vanadium concentration in the β phase is very high, then the β phase cannot transform to α' phase and then may remains partially.

The lower the temperature below the β transus temperature, the greater the amount of α phase and thus

the greater the amount of β stabilizer rejected into a decreasing amount of β phase.

At 1173 K, there was sufficient β stabilizer present that a significant amount of the β phase was retained after the quench. Further reduction in heat treatment temperature up to 1120 K results in a further decrease in the amount of retained β phase before the water quench, and the β phase was sufficiently stabilized by the vanadium rejected from the α phase that during the water quench much of the β phase was retained.

3.2 Relation between mechanical properties and heat treatment temperature

Figure 7 indicates relation between heat treatment temperature and mechanical properties. The tensile strength is almost same up to 1073 K, the strength is high for the specimen heated above 1223K. Consequently, the presense of the β phase is lowering the strength. β phase matrix causes the increase of the strength.

Elongation increases with increasing heat treatment temperature up to 1073 K, because of the increase of the β phase. Above 1223 K, the elongation and reduction in area becomes very small.

The yield strength is almost same value for various temperatures, except that at 1073 K. In the specimen heat-treated at 1073 K, the apparent grain size is small, because of the Petch relationship[4] due to the yield strength versus grain size. The very low yield strength of

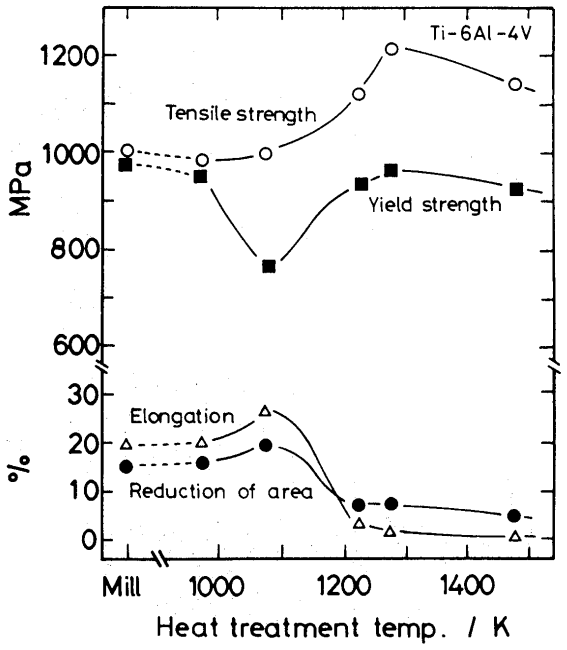

Fig. 7 Relation between heat treatment temperature and mechanical properties.

the specimen quenched from 1073 K indicates that this specimen was unstable. However, this treatment is a large fraction of α phase, and the retained β phase was enriched in vanadium. The 1073 K is just below the Ms temperature. It was shown by Bolling and Richman[5] that when the temperature was just below the Ms temperature in steels that the yield strength was anomously low. The validity of this explanation is being investigated will be reported in a subsequent publication.

Figure 8 indicates relation between hardness and heat treatment temperature. The hardness decreases with increasing heat treatment temperature in the range up to 973 K. And then, the presence of the β phase causes the relaxation of the deformation of the α phase. The hardness increase with increasing heat treatment temperature from 1073 K to 1473 K. The increase of the hardness is due to the increase of the volume fraction of the α' phase.

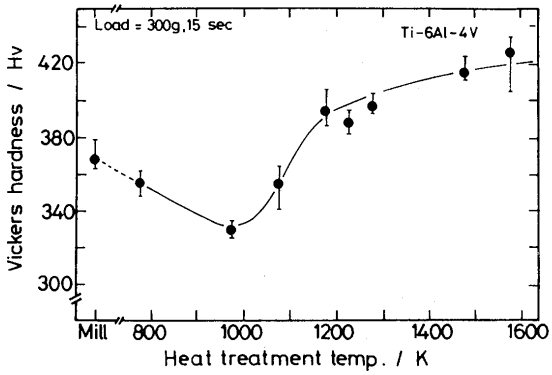

Fig. 8 Relation between heat treatment temperature and hardness.

3.3 Relation between fracture toughness, delayed cracking characteristics and microstructure

Figure 9 indicates relation between heat treatment temperature and K_{IC}. K_{IC} is same value of 40 MPa$\sqrt{m}$ in the temperature range up to 1073 K. K_{IC} is high value of 68 to 70 MPa$\sqrt{m}$ in the temperature range from 1223 K to 1473 K. The presence of the α' phase causes the increase of K_{IC}.

Figure 10 indicates relation between stress intensity factor and crack growth rate in water. The crack growth rate decreases with increasing heat treatment temperature. Mill annealed specimen and the specimen heat-treated at 973 K are consisting of $\alpha + \beta$ microstructure and the β phase is present continuously at α / α grain boundary. The crack growth rate increases with increasing volume fraction of the β phase.

The crack growth is considered to be due to the hydrogen induced cracking. The susceptibillity to hydrogen induced cracking is very high by the presence of the con-

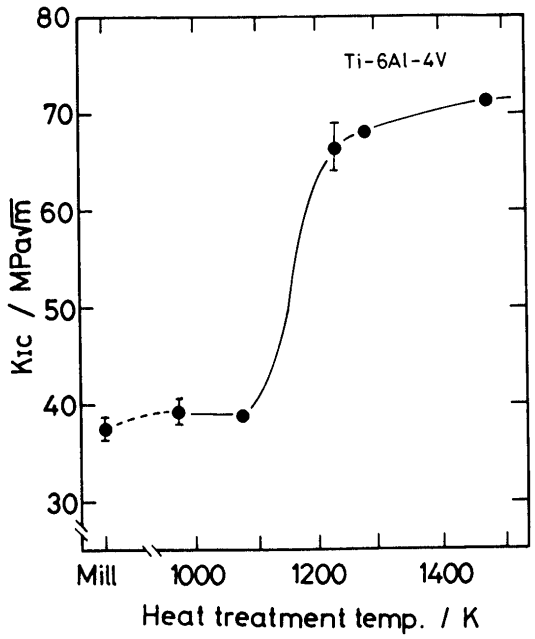

Fig. 9 Relation between heat treatment temperature and fracture toughness K_{IC}.

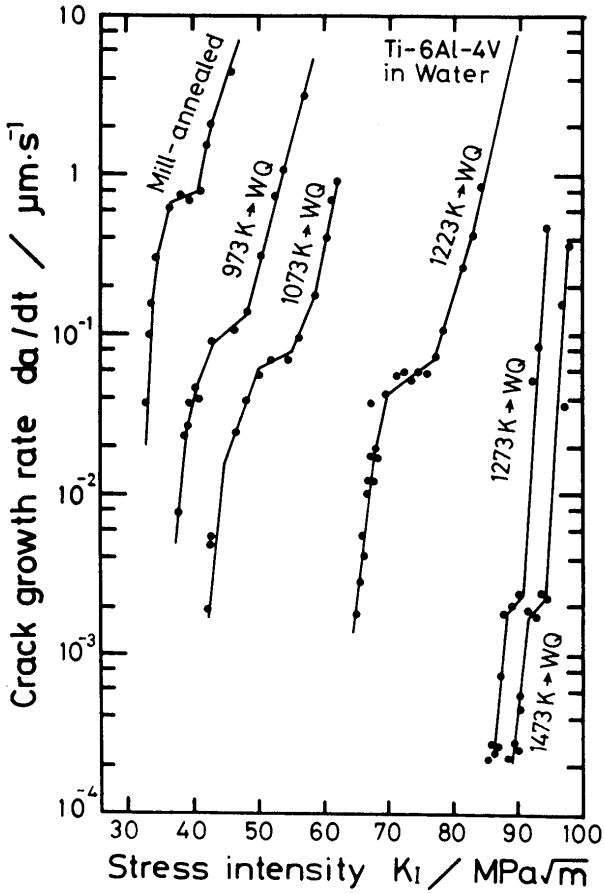

Fig. 10 Relation between stress intensity factor and crack growth rate in water for the specimens heat-treated at various temperatures.

tinuous β phase.

The specimens heat-treated at 1073 K and 1223 K are consisting of $\alpha + \alpha'$ microstructure. The crack growth rate decreases with increasing volume fraction of the α phase.

Generally, it is considered that β phase is present a little at the α / α' interface, as previously mentioned[6),7)]. Then, crack growth may be due to the β phase at α / α' interface.

The specimens heat-treated at 1273 K and 1473 K are consisting of α' microstructures. The crack growth rate is very slow, because of the α' phase. The hydrogen diffusivity in the α' phase and α phase is very low[7)] and crack growth rate is considered to be low.

4. Conclusion

Relation between microstructure of weld heat affected zone of Ti-6Al-4V alloy and mechanical properties was investigated by means of transmission electron microscopy. The results obtained in the present investigation are summarized as follows.

(1) The mill annealed specimen and the specimen heat-treated at 973 K were consisting of $\alpha + \beta$ microstructures. The β phase increased with increasing heat treatment temperature. However, the mechanical property and fracture toughness were hardly changed. The crack growth rate in water increased with increasing heat treatment temperature.

(2) For the specimen heat-treated at 1073 K to 1223 K, the microstructure was $\alpha + \alpha'$ microstructure, α' phase increased with increasing heat treatment temperature. K_{IC} increased from 40 MPa$\sqrt{m}$ to 67 MPa$\sqrt{m}$ with increasing heat treatment temperature. The crack growth rate in water of delayed cracking decreased with increasing heat treatment temperature.

(3) For the specimen heat-treated at 1273 K to 1473 K, the microstructure was α' phase. The tensile strengths in both specimen were 1100 MPa to 1200 MPa and is higher than that of the mill annealed specimen. The crack growth rate of the delayed cracking in water is very slow, because of the α' microstructure.

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