Effect of Microstructure on High-Cycle Fatigue Properties of Ti-6Al-4V Alloy Forging at Cryogenic Temperatures

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Backgrounds

Titanium alloys have high specific strength and many advantageous physical properties, such as low conductivity and high electric resistivity when used as cryogenic structural components. For example, **titanium alloys are used as the material for the Japanese rocket engines** that serve as high-performance propellant system using liquid hydrogen and liquid oxygen. The engine parts of titanium alloy are exposed to liquid hydrogen and used under tension–tension loading condition during operation. Therefore, **it is very important to evaluate the fatigue performance** for titanium alloys to be used for the engine parts.

Ti-6Al-4V alloy is one of the most popular α +β titanium alloy and used in varieties of applications. It is well known that **the mechanical properties of α +β titanium alloys are very sensitive to the microstructure** and that of α +β titanium alloys strongly depends on both the processing history and the heat treatment.

When titanium alloy is used for structural components, it is generally used for titanium alloy which has **the equiaxed or the bimodal microstructure**. On the other hand, it was reported that the large-size Ti-6Al-4V alloy with **the lamellar microstructure** is more advantageous for high cycle fatigue strength than equiaxed microstructure because the turbo pump is made from the forged large-size titanium alloy of about φ 180×L140 by cutting.

Objaective of this study

we obtained the high-cycle fatigue properties of the bimodal and lamellar α microstructures for the Ti-6Al-4V alloy at cryogenic temperatures and discussed the effect of the microstructure on high-cycle fatigue properties at cryogenic temperatures.

Material used in this study

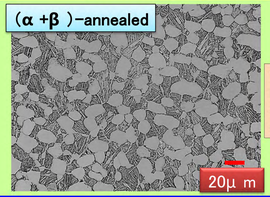
Chemical compositions of Ti-6Al-4V alloy forging (mass %).

	N	O	H	Fe	C	Al	V	Y	Other each	Other Total	Ti
Products analysis	0.005	0.20	0.0069	0.28	0.01	6.68	4.35	<0.001	<0.10	<0.40	Bal.
Require-ment	0.05	0.20	0.0125	0.30	0.08	5.50 – 6.75	3.50 – 4.50	0.005	<0.10	<0.40	Bal.

Ingot size (Forging) : φ 350×L200 (Forging ratio:2.4)
Heat treatment : 7.2ks at 1213 K followed by water-quenching and for 10.2ks air anneal at 978 K
AMS4928(Aerospace Material Specification)

Optical micrograph of Ti-6Al-4V alloy forging

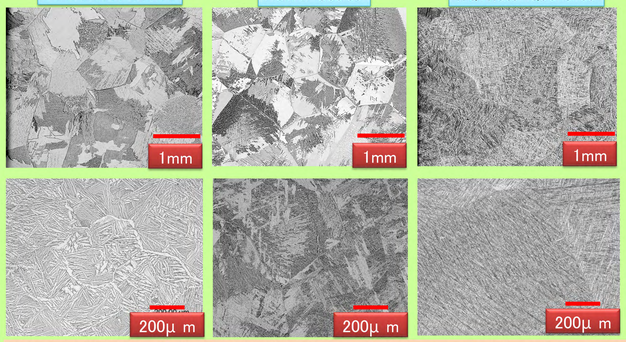
(α +β)-annealed



The microstructure of the (α +β)-annealed material has bimodal microstructure which consists of equiaxed-α (about 20 μ m) and α +β lamellar microstructure.

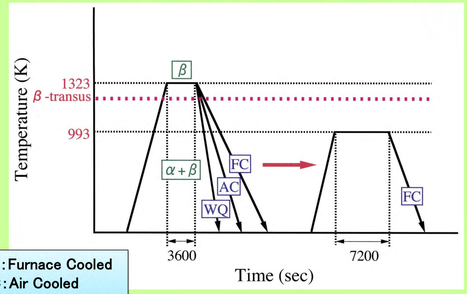
Optical micrographs of Ti-6Al-4V alloy (β -annealed)

FC : Furnace Cooled | AC : Air Cooled | WQ : Water Quenched



The β -annealed materials, FC, AC and WQ materials has lamellar microstructure. The width of α lamellar in FC material is from 4 to 12μm. and that of AC material from 2 to 3μm. The WQ material shows the finer α lamellar structure. The prior-β grain structure was observed in FC, AC and WQ materials and its size in each material was roughly about 900～2000μm, 700～1800 μm and 600～ 1500μm, respectively. The prior-β grain structure is consists of several colonies.

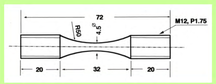
Heat treatment conditions (β -annealed)



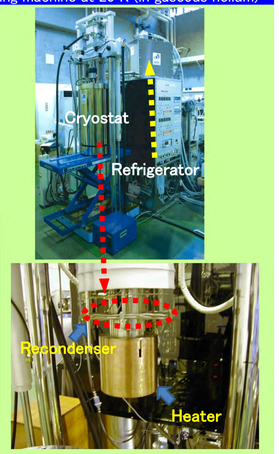
FC : Furnace Cooled
AC : Air Cooled
WQ : Water Quenched

Heat treatment: The β -annealed materials were heated for 3.6ks at 1323 K (above β -transus temperature), and then furnace-cooled (FC), air-cooled (AC) and water-quenched (WQ). Finally, FC, AC and WQ materials were followed by 7.2ks furnace-cooled at 993 K.

Fatigue specimen (Hourglass-type)



Fatigue testing machine at 20 K (in gaseous helium)

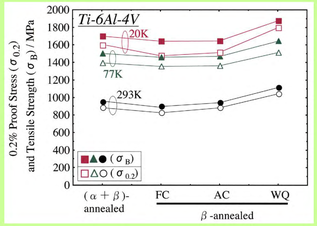


High-cycle fatigue testing conditions

- **Testing machine:**
  ○Servohydraulic model ○Dynamic load capacity ±100kN
- **Testing conditions:** ○ Sinusoidal cyclic load
  ○ Load control
  ○Stress ratio : R=0.01 (σ min/σ max tension–tension
- **Testing temperature:** ○20 K (in gaseous herium),
  77 K (liquid nitrogen) 、293 K (in laboratory air)
- **Testing frequency:** ○20 K (GHe) : 5Hz～15Hz、
  77K and:293 K : 10～15Hz
- **Stepwise test:** ○The specimens which had survived 10^7-cycles at 20 K and 2×10^7-cycles at 77 and 293 K were further tested under increased load until fracture occurred

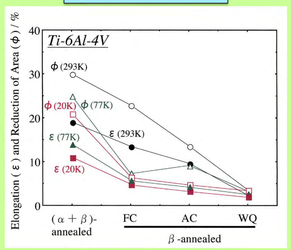
(RESULTS) Tensile properties

Solid: Tensile strength
Open: 0.2% proof stress



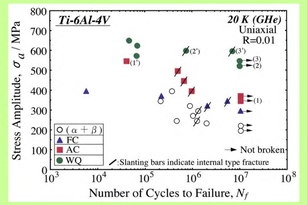
The 0.2% proof stress and tensile strength of the FC and AC materials at each temperature were slightly lower than those of (α +β)-annealed material. However, those of WQ material were higher than (α +β)-annealed material.

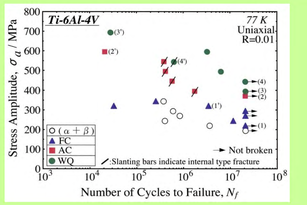
Solid: Elongation
Open: Reduction of area

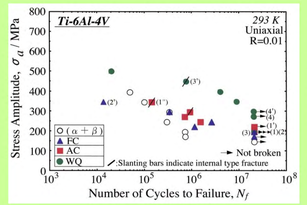


The elongation and the reduction of area for the each β -annealed material at each temperature were lower than those of (α +β)-annealed material.

S-N curves at 20, 77 and 293 K



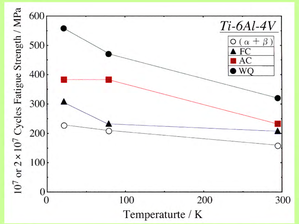




The S-N curves of each material shifted to the higher stress levels, i.e., the longer life side, with decreased test temperature. It is clear that the fatigue strengths of the β -annealed materials are higher than those of the (α +β)-annealed material at all test temperatures. Especially, WQ material were significantly increased.

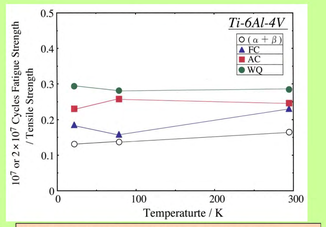
Temperature dependence of fatigue strengths

The 10^7 or 2×10^7cycles fatigue strength (FS) as a function of test temperature



The FS increase in the order of the (α +β), FC, AC and WQ materials. In 20 K, the FS of FC, AC and WQ materials is 1.4, 1.7 and 2.4 times compared with those of the (α +β)-annealed material.

Ratio of the 10^7 or 2×10^7cycles fatigue strength to tensile strength as a function of test temperature

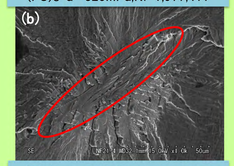


This figure shows the temperature dependence on fatigue strength of the each structure. It can be seen empirically that FS remains proportional to tensile strength even at cryogenic temperatures. The ratios of FS to TS increase in the order of the (α +β)-annealed, FC, AC and WQ materials. The FS to the TS of the each β -annealed materials are higher than those of the (α +β)-annealed material at all test temperatures.

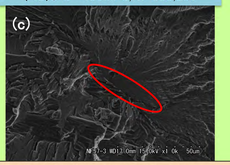
SEM micrographs of fracture surface of high-cycle fatigue specimen at 20 K

(α +β)σ a =300MPa,Nf=1,255,451

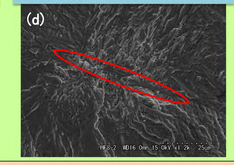
(FC)σ a =325MPa,Nf=1,977,411



(AC)σ a =450MPa,Nf=633,291



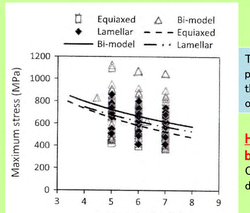
(WQ)σ a =600MPa,Nf=6,357,028



The internal fatigue crack initiation sites of the (α +β) annealed materials are composed of one or more facets and the size of these individual facets match well the α grain size, as shown in Figure (a). Those of FC and AC of the β -annealed materials consist of one more facets, as shown in Figures (b) and (d). Each facet can be matched to an according to α platelet its morphology and size. A few cases exhibit a larger facet which reflects the colony or the β -prior grain structure. On the other hand, that of WQ material is a lamellar α , as seen in Figure (d). As mentioned above, the internal fatigue crack initiation sites of the (α +β) annealed and the β -annealed materials related the α grain structure.

Effect of the microstructure on high-cycle fatigue properties

The 10^7-cycles fatigue strengths at 20 K decrease in the order of WQ, AC, FC and the (α +β) annealed materials. This result means that the high-cycle fatigue strengths of the β -annealed materials are much higher than that of the (α +β) annealed one in the present forging. However, the opposite results were reported in the past many studies. This is considered to be the rolling or the forging procedure affecting texture.
Further investigations are clearly needed to analyze the crystallographic orientation of a facet formed at a fatigue crack initiation sites in a specimen fatigue tested by electron backscatter diffraction (EDSD) in a SEM.



Though an analysis on microstructure and high-cycle fatigue properties of Ti-6Al-4V alloys which were selected from literature, the effects of microstructure types and microstructure parameters on high-cycle fatigue properties were investigated systematically.

High-cycle fatigue strength (1972–2013)
bimodal > lamellar > equiaxed
Generally the High-cycle fatigue strengths of different microstructures decrease in the order of bimodal, lamellar and equiaxed microstructure.

G. Q. Wu, C. L. Shi, W. Sha, A. X. Sha and H. R. Jiang, Materials and Design, **46**, 668–674 (2013)

SUMMERY

The effect of microstructure on the high-cycle fatigue properties of Ti-6Al-4V alloy forging at cryogenic temperature were investigated using four materials with different microstructure. One of them was α +β annealed and has bimodal microstructure which consists of equiaxed-α and α +β lamellar microstructure. Three other materials were water quenched (WQ), air cooled (AC) or furnace cooled (FC) after β -annealing. The β -annealed materials have lamellar microstructure and α lamellar width increase in the order of WQ, AC and FC materials. The 10^7-cycles fatigue strengths at 20 K decrease in the order of WQ, AC, FC and the α +β annealed material. This result means that the high-cycle fatigue strengths of β -annealed materials are much higher than that of α +β annealed one in the present forging. However, the opposite results were reported in the past many studies. This is considered to be the rolling or the forging procedure affecting texture.

Further investigations are clearly needed to analyze the crystallographic orientation of a facet formed at a fatigue crack initiation sites in a specimen fatigue tested by electron backscatter diffraction (EDSD) in a SEM.

LE-7A Engine (JAXA)