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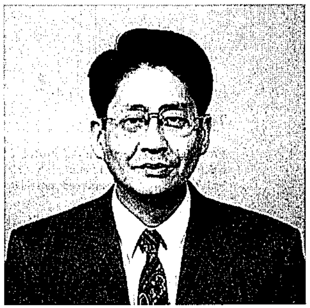
Titanium Alloy Bar Suitable for Highly Efficient Wear-Resistance Treatment

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Abstract

To give the wear-resistance to titanium intake valve by simple oxidation treatment, the oxidation condition and the microstructure of Ti-6Al-4V bar were studied. The wear test using a valve simulator shows that the wear of the face oxidized at 820℃ for 1 and 4h in air is superior to that of ferrous valve. The best microstructure of Ti-6Al-4V bar is an acicular structure with the prior β grain size of 30 to 60 μm in average, which prevents distortion during the oxidation treatment and has excellent mechanical properties.

1. Introduction

Use of titanium is one of the means[1] to realize good fuel efficiency and design high power engines through weight reduction of engine components because of its small specific gravity, high strength and heat resistance. But the cost performance of titanium components is inferior to steel components, and for this reason, actual application of titanium is limited to racing cars and special limited-version vehicles[1-3]. Among a wide variety of engine components, valves, which move up and down at high speeds, form one of the best fields of application where the advantage of the weight reduction by use of titanium can be fully exploited. The material properties of titanium alloys are suitable particularly for an intake valve, which is larger than an exhaust valve and moves in a longer stroke so as to draw a large amount of air into a cylinder. For this reason, the effect of weight reduction is especially significant with the intake valve. With respect to the exhaust valve, on the other hand, presently available heat resistant titanium alloys are considered insufficient in terms of high temperature characteristics required for the application, and TiAl-base new materials will be developed for the exhaust valve in future[4].

The face and stem of engine valves are exposed to a very severe wear condition, and therefore, tufftriding or soft nitriding treatment is applied to engine valves of heat resistant steels[5]. In the case of engine valves of titanium alloy valves, some of them are treated, for example, with thermal spray of molybdenum at the stem and hard facing of a carbide-dispersed titanium-base alloy at the face[2,3]. However, on the top of the high cost of the very titanium alloy bars, the costs of these wear-resistance treatments have made the total cost of the titanium alloy valves almost prohibitive.

Looking for a radical solution from the standpoint of reducing the cost of the wear-resistance treatment, in the first place, the authors selected oxidation treatment in normal atmosphere as a measure to give wear resistance to the titanium alloy intake valves and studied the conditions of the treatment. A problem with the oxidation treatment is that, when a bar of a generally produced α+β titanium alloy having equiaxed microstructure is used, the oxidation treatment may cause intolerably large distortion (bending) of the valve stem during heat treatment. In this respect, the metallographic structure of titanium alloys was studied in order to discover a way to

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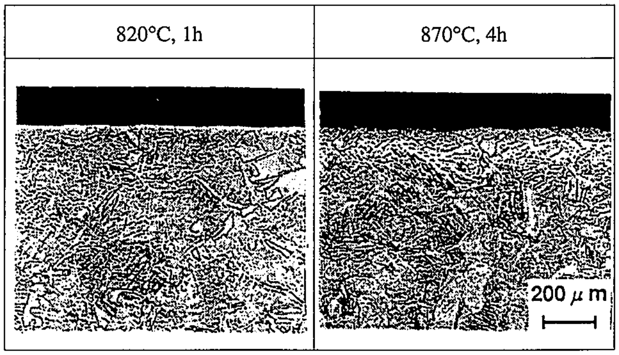
overcome the bending problem. Ti-6Al-4V alloy was selected as the α+β alloy for the study, in consideration of its excellent mechanical properties in the temperature range from the room temperature to 300°C, in which the intake valves operate, and its wide applicability.

2. Optimum Oxidation Condition

What is characteristic about the oxidation of titanium materials is that a hardened layer called α case, which is shown in **Photo 1** as a whitish band near the surface, is formed near the surface. The α case is formed beneath the titanium oxide scale (not shown in Photo 1) and is a part of the base metal in which much oxygen is contained in solid solution. It happens that the α case has wear resistance far superior to the scale, and when formed thick, wear resistance is enhanced, although surface roughness is increased and a polishing process is required.

2.1 Test Method

Fig. 1 shows manufacturing processes of an engine valve. The raw material is a Ti-6Al-4V bar 7 mm in diameter and it is electrothermally heated and upset-forged into a rough valve shape, like in the case of the heat resistant steel valve. The samples for the test were annealed for stress relieving, machined into the final shape, then oxidized under different conditions designed for the test, and finally oxide layers were removed. The shape and dimension of the sample valves used for the test are also shown in Fig. 1, which corresponds to a small size valve for 4-valve engines. Valves of conventional heat resistant steel were also tested for comparison purposes. The steel used here was SUH11 (Fe-8Cr-1.5Si-0.5C), the material most widely used for the intake valves in Japan. The manufacturing processes of the SUH11 valves are nearly the same as those of the Ti-6Al-4V valves, except that the wear-resistance treatment is a tufftriding treatment at 580°C for 30 min.


820°C, 1h

870°C, 4h

Photo 1 Subsurface hardened layer (α case) of oxidized Ti-6Al-4V

	Titanium valve	Steel valve
Material of bar	Ti-6Al-4V (studied)	SUH11 (Fe-8Cr-1.5Si-0.5C)
Wear-resistance treatment	Oxidation at different condition	Tufftriding (soft nitriding)
Weight	26g	45g

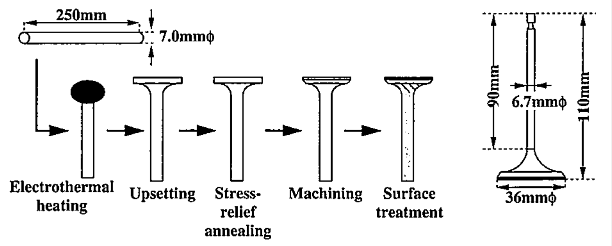
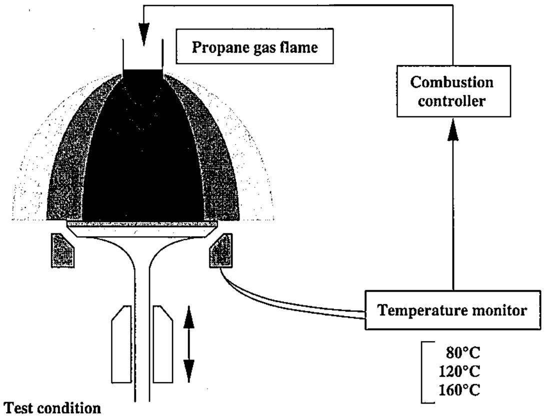


Fig. 1 Manufacturing processes of engine valves



Test condition

Valve face roughness: 1.0-1.5 μmRa, 1.5-3.0 μmRz
f=3,000rpm, Number of contact 8×10^5, Valve face & seat: No lubrication
Valve seat: Fe-Cu-C sintered material, Stem & valve guide: SAE 10W-30 oil

Fig. 2 Schematic illustration of valve simulator

A valve simulator, which is schematically shown in **Fig. 2**, to accelerate the wear of valve portions and the engine components contacting the valve, was used for evaluating wear resistance. The wear of a valve face and a valve seat was evaluated by measuring their thickness change before and after the test. The valve seats used for the test were made of a sintered Fe-C-Cu alloy generally used for the application in Japan. The repetition speed of the valve simulator is 3,000 times a minute, which corresponds to 6,000 rpm in a real engine. The valves and valve seats were heated for the test with propane gas flame to 80, 120 and 160°C as measured at the base of the valve seats.

2.2 Test Results

An oxidation treatment at 720°C for 1 h of the titanium alloy valve resulted in only insufficient wear resistance of the valve face, roughly the same wear resistance as "No surface treatment" in **Fig. 3**. Although oxidation treatment at 770°C for 1 h brought about good wear resistance, the hardened layer was only 2 to 3 μm thick and good durability could not be expected. Oxidation at 870°C for 1 h resulted in undesirably rough surface. Finally, perfectly acceptable

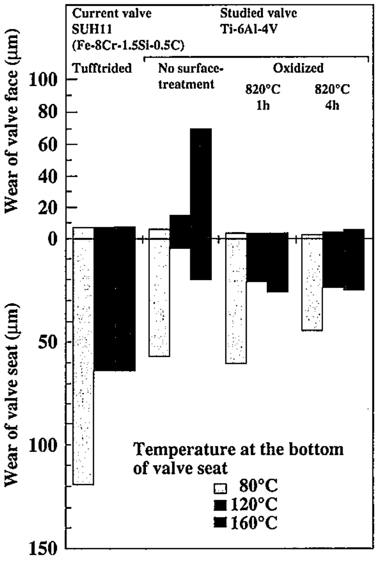


Fig. 3 Results of wear test using valve simulator

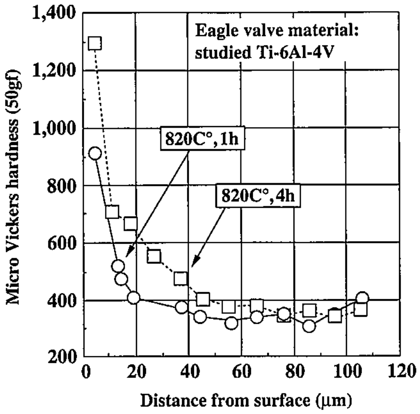


Fig. 4 Surface hardness profile of titanium alloy engine valves after oxidation treatment

results were obtained through oxidation at 820°C for 1 and 4 h.

Fig. 4 shows Vicker's hardness profile (load of 50 kg) along depth of oxidation-treated titanium valve samples. The thickness of the layer hardened to 600 Hv or more was about 10 µm after an oxidation at 820°C for 1 h. These values of 600 Hv and 10 µm are almost identical to the respective values used in the generally used definitions of the hardened layer and its thickness of the heat resistant steel valves. The thickness of the hardened layer of the titanium valve increased to roughly 22 µm when the oxidation time was 4 h.

Fig. 3 shows the wear of the valves and valve seats. The titanium valves showed not only smaller wear than that of the steel valves, but also remarkably smaller wear of the valve seats. The wear of the steel valves and valve seats were so large that the service life of an engine would have expired after a valve simulator test of 4.4 h, which demonstrates how tough the test condition was. It was also noted that the noise level of the titanium valves during the wear test was considerably lower compared with that of the steel valves.

3. Titanium Alloy Bar Suitable for Oxidation Treatment

Formation of acicular structure of Ti-6Al-2Sn-4Zr-2Mo-0.1Si obtained through heating or forging at a β range temperature has been proposed as an attempt to achieve the creep property required of an exhaust valve[1]. There are, however, only a limited number of studies on the influence of the microstructure of titanium alloy bars on the properties of intake valves, and there is no study at all on the microstructure of titanium alloys in relation especially to the use of oxidation for enhancing wear resistance. Deformation (bend) of valves during chemical treatment may sometimes amount to an intolerable level, and the main factors having influence on the deformation include chemical composition, microstructure, stress relieving annealing, oxidation temperature, shape of the valve itself and the posture of the valve during heat treatment.

As was explained, a serious problem of the oxidation treatment is that, when the widely used Ti-6Al-4V alloy having fine equiaxed microstructure undergoes the treatment, large distortion beyond a tolerable range is created by the heating, and this is probably the most significant reason why many researchers and process developers gave up oxidation as a method of wear-resistance treatment.

3.1 Test Method

A simple bend test was carried out for the purpose of examining the influence of microstructure on the bending of a valve caused by its own weight. In order to prevent oxidation film formed on the valve surface from interfering with the measurement of straightness, the heating for the bend test was done in a vacuum. The stem of a sample valve was supported at two points 80 mm away from each other and the valve to be tested was heated to about 820°C, the optimum oxidation temperature (see **Fig. 5**), then the deviation from straightness was measured as shown in **Fig. 6**. The sample valves used for the test, microstructures of which are shown in **Photo 2**, were the same as those used in the test described in section 2. The acicular structure (Photo 2 A and C) is obtained through heating to or working in the β phase temperature range, and the fine equiaxed crystal (Photo 2 B) and the coarse equiaxed crystal (Photo 2 D) are formed through annealing in the α+β phase temperature range under different temperature, time and cooling rate conditions.

3.2 Test Results

The acicular structure consisting of prior β grains 300 to 1,000 µm in size did not show any deformation at all up to 800°C, as shown with "Colony" in **Fig. 7**. Since ductility of the acicular structure is low, however, when a Ti-6Al-4V bar in coil is straightened, cracks may form on the surface. A sample of the coarse equiaxed grains having an α grain size of about 10 µm ("Coarse equiaxed" in Fig. 7) showed a considerably smaller bend of the stem compared with another of the fine equiaxed grains ("Conventional" in Fig. 7) having an α grain size of about 2 µm. However, even the smaller bend of the coarse equiaxed structure was unacceptable in actual use, and another problem is that its fatigue strength is as low as 80% or so of that of the fine structure[6].

The acicular structure having α grains 30 to 60 µm in size ("Studied" in Fig. 7), which was formed through working at a comparatively low temperature in the β phase temperature range, is considered the best structure in terms of the distortion during the oxidation treatment and mechanical properties. The bend of this structure was nearly the same as that of the colony structure having larger β grains. In addition, it has excellent mechanical properties as explained in

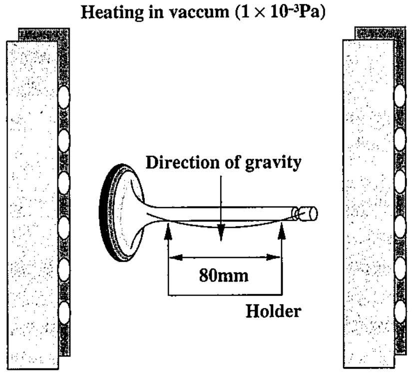


Fig. 5 Schematic illustration of bend test

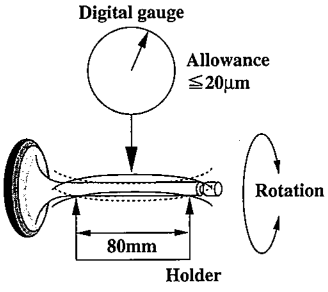
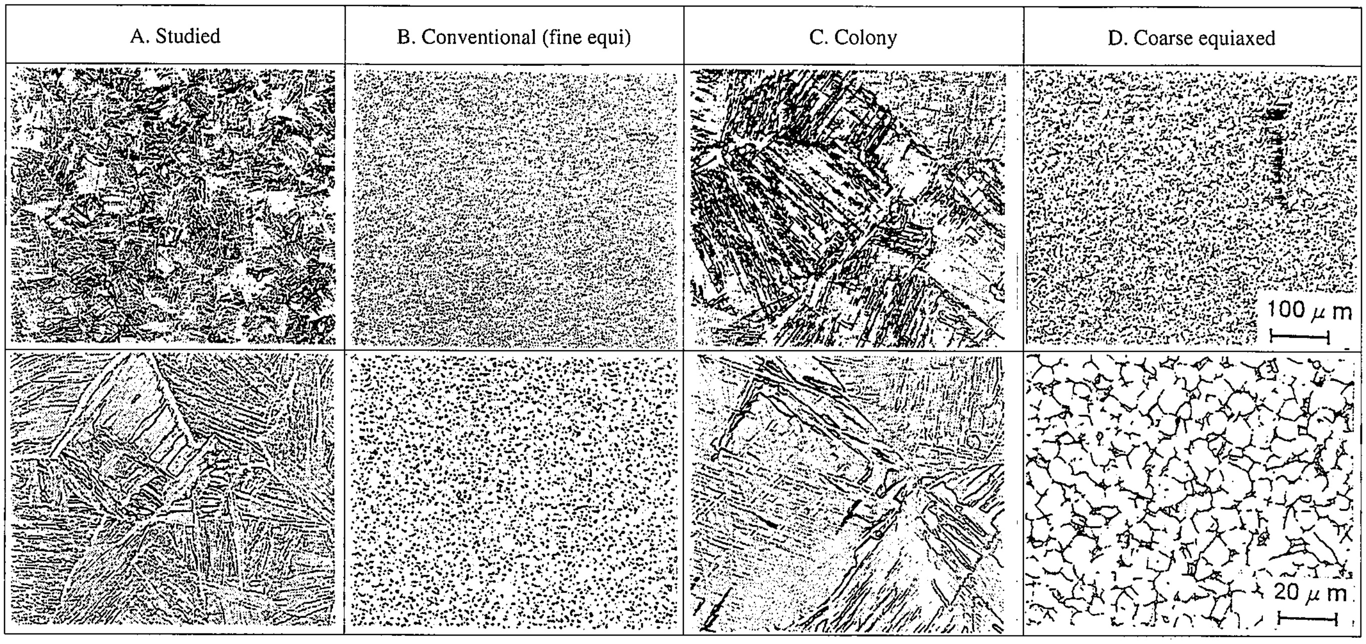


Fig. 6 Measurement method of valve stem bend



A. Studied

B. Conventional (fine equi)

C. Colony

D. Coarse equiaxed

Photo 2 Microstructures of Ti-6Al-4V bars (in traverse cross section)

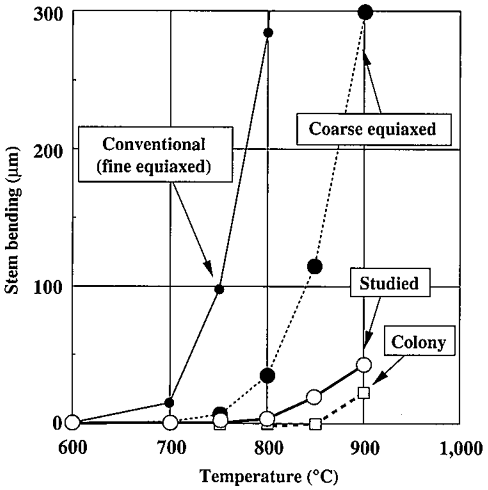


Fig. 7 Relation between heating temperature and valve stem bend

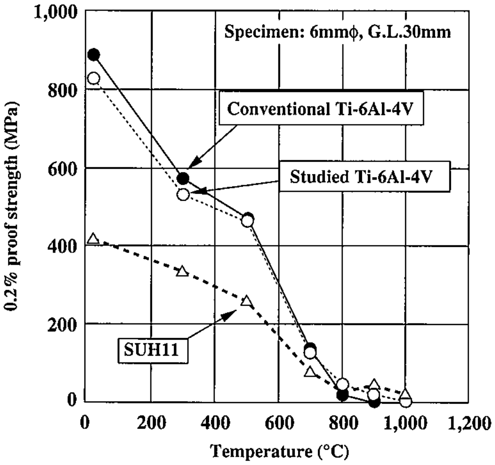


Fig. 8 Results of high temperature tensile tests (0.2% proof stress)

the following section. Supposing that the tolerable bend of the stem is 20 μm or less, an oxidation treatment up to 840°C can be applied to this most desirable structure. On the other hand, a heat treatment at 700°C or higher cannot be applied to the fine equiaxed structure, and this means that good wear resistance cannot be obtained with this structure.

The posture of the valves during the heat treatment should be given due consideration in actual oxidation treatment; the bend is minimized when the valve stems are positioned perpendicularly.

4. Mechanical Properties of Titanium Alloy Bars

Tensile characteristics of two different microstructures of the Ti-6Al-4V alloy and those of SUH11 at different temperatures up to 1,000°C are compared in **Figs. 8 to 11**. The studied Ti-6Al-4V (having the fine prior β grains shown in Photo 2 A) showed almost the same characteristics at every test temperatures as the ordinary Ti-6Al-4V (having the fine equiaxed grains shown in Photo 2 B) did,

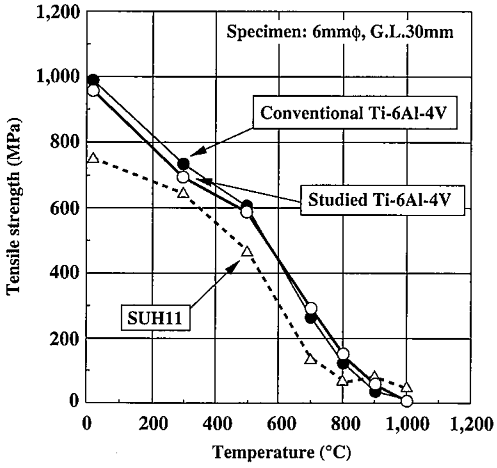


Fig. 9 Results of high temperature tensile tests (tensile strength)

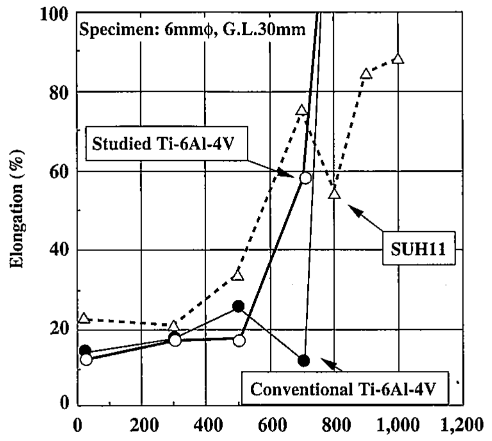


Fig. 10 Results of high temperature tensile tests (elongation)

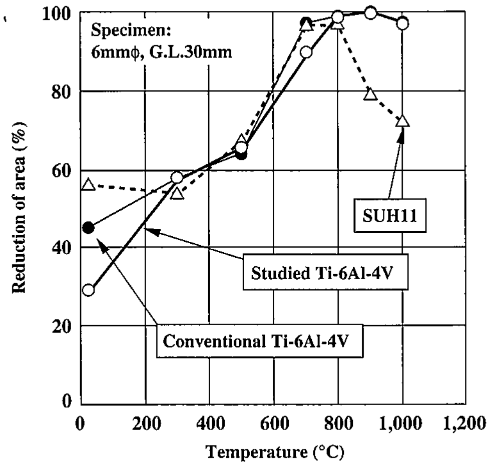


Fig. 11 Results of high temperature tensile tests (reduction of area)

and the 0.2% proof stress and tensile strength of the former were higher than those of SUH11 at temperatures up to 800°C.

Figs. 12 to 15 show the rotating bending fatigue properties of the sample valves at the room temperature, 300°C and 500°C. As seen in Fig. 12, the fatigue strength of the studied Ti-6Al-4V after a repetition of 10^7 cycles was higher at any of the temperatures than that of SUH11 shown in Fig 15. It is also considerably higher than that at 500°C of the fine equiaxed structure (see Fig. 14). As is understood from a comparison of Figs. 12 and 13, an oxidation treatment at 820°C for 1 h results in lowering of fatigue strength at any of the test temperatures, at the room temperature in particular. The fatigue strength after oxidation is lower at the room temperature than at 300 or 500°C. The deterioration of the fatigue strength at the room temperature is presumably attributable to the fact that the α case resistant against wear does not have sufficient strength at the room temperature.

The fatigue strength of the oxidized Ti-6Al-4V is, however, considerably higher than the estimated stress (35 to 70 MPa) on the fillet of the head of a valve[1]. If the stress imposed on the fillet is close to the above fatigue strength, the α case of the portion has to be removed, since wear resistance is not particularly required there.

Creep characteristics at 500°C of Ti-6Al-4V and SUH11 are compared in **Fig. 16**. The steady state creep rate of the Ti-6Al-4V having the fine prior β grains is superior to either of SUH11 or the Ti-6Al-4V having the fine equiaxed grains. **Fig. 17** shows the Charpy im-

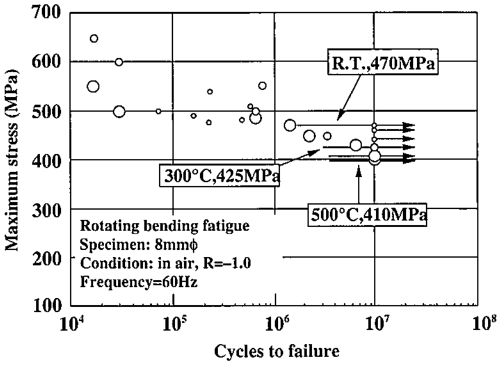


Fig. 12 S-N curves of studied Ti-6Al-4V

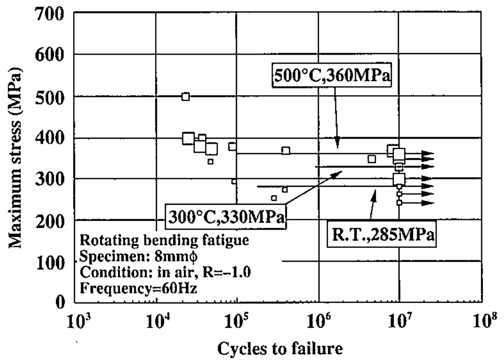


Fig. 13 S-N curves of studied Ti-6Al-4V after oxidation treatment at 820°C for 1 h

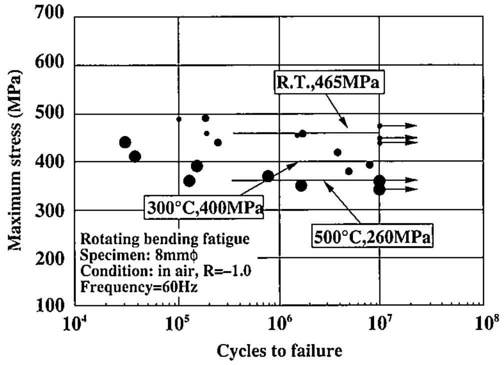


Fig. 14 S-N curves of ordinary Ti-6Al-4V

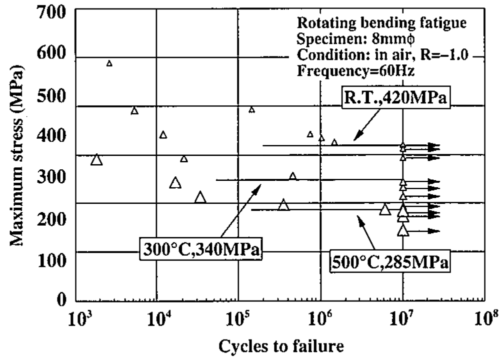


Fig. 15 S-N curves of SUH11 (Fe-8Cr-1.5Si-0.5C)

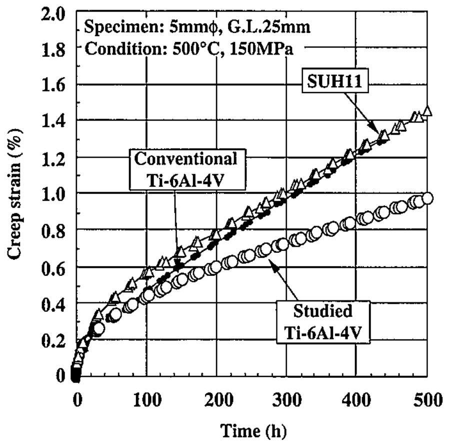


Fig. 16 Creep behavior of studied Ti-6Al-4V

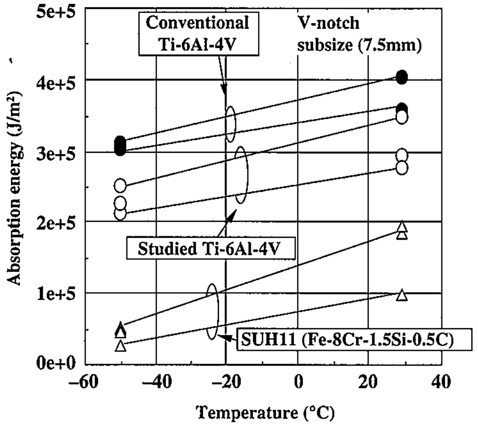


Fig. 17 Charpy impact characteristics of studied Ti-6Al-4V

pact characteristics at −50 and +28°C. The absorbed energy of the Ti-6Al-4V of the fine prior β grains is sufficiently large at either of the temperatures.

5. Summary

Oxidation conditions and the microstructure of Ti-6Al-4V were studied in view of applying simple oxidation to titanium intake valves as wear-resistance treatment. The essence of the results is as follows:

(1)Heating to 820°C in normal atmosphere for 1 and 4 h constitutes the optimum oxidation condition. A test using a valve simulator made it clear that the fatigue characteristics of the titanium valve treated under the optimum oxidation condition were very excellent compared with the conventional steel valve. Moreover, the wear of valve seats is far smaller in the case of titanium valves compared with steel valves.

(2)The microstructure most suitable for intake valves is the acicular structure having a prior β grain size of 30 to 60 μm. This structure prevents bending of the valve stem from occurring during the oxidation treatment and has excellent mechanical properties.

(3)A combination of the oxidation treatment with the above microstructure opens a new way to attain a high cost performance titanium intake vale. Shortly, the titanium valves manufactured by this method will largely contribute to performance enhancement such as improved fuel efficiency of commercially marketed automobiles.

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