SPECIAL ISSUE

RESEARCH REPORT

Influence of heat-treatments on the microstructure and mechanical properties of a commercial beta titanium alloy, Ti-13V-11Cr-3Al

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The effects of aging after solution-treatment and aging after cold-working on the microstructure and mechanical properties of a commercial beta titanium alloy Ti-13V-11Cr-3Al were investigated. In the aging after solution-treatment, preferential alpha precipitation on beta grain boundaries is remarkable in the aged microstructure and, with increase in aging time, strength increases, however, ductility decreases greatly due to the development of grain boundary cracking. The grain boundary cracking is caused by the preferential precipitation of alpha phase on the beta grain boundaries. In the aging after cold-working, cold-working remarkably promotes aging response and greatly improves strength-ductility balance after aging through suppressing preferential precipitation of alpha phase on grain boundaries and getting more uniform and finer aged microstructure. In this heat-treatment, higher reduction in cold-working and lower temperatures in aging are preferable to the improvement of mechanical properties.

Keywords: titanium alloy, aging, cold-working, mechanical properties, microstructure

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1. Introduction

Beta titanium alloys have high potential for expanded applications not only for its excellent mechanical properties but also for its cost advantages from good cold formability. A number of research have been conducted on formability, heatability, mechanical properties and applications of the beta titanium alloys^{1)~12)}. Mechanical properties of commercial beta titanium alloys strongly depend on aged microstructure composed of beta matrix and precipitated alpha phase. In order to get better balance of mechanical properties, it is important to understand the aging behavior of beta titanium alloys i.e. characteristics of alpha precipitation, hardening and variation of microstructure with aging treatments.

This research investigates the effect of aging treatments on the microstructure and mechanical properties of a commercial beta titanium alloy Ti-13V-11Cr-3Al.

2. Experimental Procedures

The Ti-13V-11Cr-3Al alloy was a 30 mm diameter bar that was hot-rolled, solution-treated at 1173 K for 7.2 ks and air-cooled. The chemical compositions of this alloy are shown in **Table 1**. Heat-treatments were conducted on the specimens after cold-working with from 30% to 90% reduction of the bar using a rotary swaging machine. The aging treatment after solution-treatment at 1123 K for 3.6 ks is abbreviated as STA and the aging treatment without solution-treatment after cold-working is abbreviated as CWA hereafter.

Table 1 Chemical compositions of titanium alloy used (mass%)

V	Cr	Al	Fe	O	C	N	H	Ti
13.68	10.58	3.03	0.17	0.166	0.013	0.011	0.0020	bal.

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Vicker's hardness measurement, microstructure observations using an optical microscope and an electron microscope, as well as uniaxial tensile testing, were performed on the above specimens. Also, a X-ray diffraction analysis was used to detect alpha phase precipitation.

Tensile testing was performed at room temperature at a crosshead speed of 1.7×10^{-3} mm/s. The tensile specimens had a gauge size of 4.0 mm in diameter and 15.0 mm in length and a grip of 7.0 mm in diameter.

3. Results and Discussion

3.1 Age Hardening

Fig. 1 shows the variations of hardness of the specimens aged at 700 K, 750 K and 800 K in STA with aging time. There was a tendency that the hardness of specimens aged at higher temperatures rose earlier but the higher hardness was attained with lower aging temperatures. In aging at every temperature, it took over megaseconds to attain the maximum hardness value.

3.2 Microstructure

Fig. 2 shows the variations of microstructures with aging temperatures of 700 K and 800 K and aging time. These photos show that alpha phase precipitated preferentially on beta grain boundaries and like colonies in beta grains. It is also indicated that, compared with aging at 700 K, aging at 800 K yielded more rapid aging response that corresponds to more rapid increase of hardness because nose temperature in TTT diagram of this alloy is around 800 K¹³⁾, however, it produced larger alpha precipitates therefore the attained hardness was lower as shown in Fig. 1.

Fig. 1 Variations of hardness of the specimens aged at 700 K, 750 K and 800 K in the heat-treatment of aging after solution-treatment with time of aging.

On the solution-treated specimens, single beta phase was confirmed through a X-ray diffraction analysis and, on the aged specimens, reflections corresponding to any other phases except alpha and beta phases were not detected.

3.3 Tensile Properties and Precipitated Alpha Phase in STA

Fig. 3 shows the variations in ultimate tensile strength (σ_B), 0.2% proof stress ($\sigma_{0.2}$) and reduction in area (RA) with aging time. Aging temperature was 750 K. Ultimate tensile strength and proof stress increased with increase in aging time and attained to the highest values after aging for over megaseconds that correspond to the variations of hardness with aging as shown in Fig. 1. The highest tensile strength level was about 1.4 GPa. On the other hand, the ductility decreased greatly with increase in aging time.

Fig. 2 Variations of microstructures with aging temperatures and aging time.

a): aged at 700 K for 360 ks, b): aged at 700 K for 1 Ms, c): aged at 800 K for 100 ks and d): aged at 800 K for 360 ks.

Fig. 3 Variations in ultimate tensile strength (σ_B), 0.2% proof stress ($\sigma_{0.2}$) and reduction in area (RA) with aging time. Aging temperature was 750 K.

Fig. 4 Deformation traces formed around an alpha colony on the surface of a specimen deformed by using the device of SEM in-situ observation. The specimen was aged at 750 K for 100 ks. Loading direction is vertical.

Fig. 4 shows deformation traces formed around an alpha colony on the surface of a specimen deformed by using the device of SEM in-situ observation. The specimen was aged at 750 K for 100 ks. The fact that the deformation traces turned around the alpha colony indicates the increase of resistance to deformation by alpha precipitates.

Fig. 5 shows the void formation around alpha precipitates in the longitudinal section of the central portion of the specimen that was aged at 750 K for 200 ks and deformed just before break in tensile test. This photo indicates that the void was formed by the intersection of alpha precipitates and a shear band.

Fig. 6 shows the variations of fracture surfaces of the specimens aged at 750 K with aging time. All the fracture surface of the solution-treated specimen was covered with dimples and the areal fraction of flat facets on fracture surfaces increased with increase in aging time. After 3.6 megaseconds aging, all the fracture surface was covered with flat facets. Therefore, the increase of flat facets on the fracture surfaces would correspond to the decrease of ductility with aging.

Fig. 7 shows the longitudinal section of the central portion of the tensile specimen aged at 750 K for 200 ks and deformed just before break. **Fig. 7 b)** shows the high magnification observation of the microcrack shown in **Fig. 7 a)** and it indicates that these microcracks were grain boundary cracks caused by preferential precipitation of alpha phase on beta grain boundaries. Therefore, the fracture of the specimen would be caused by joining the grain boundary cracks that were formed before break and these grain boundary cracks correspond to the flat facets on the fracture surfaces shown in **Fig. 6**.

Thus, alpha precipitates play an important role not in

Fig. 5 Void formation around alpha precipitates in the longitudinal section of the central portion of the specimen that was aged at 750 K for 200 ks and deformed just before break in tensile test. Loading direction is vertical.

Fig. 6 Variations of fracture surfaces of the specimens aged at 750 K with aging time.

a): as solution-treated, b): 65 ks, c): 200 ks, d): 360 ks and e): 3.6 Ms.

strengthening but also in fracture of this alloy. It is indicated that, with development of aging, grain boundary cracking becomes a prevailing fracture mechanism and causes great loss of ductility¹⁴⁾. Therefore, in order to get better balance of strength and ductility, it would be important to suppress preferential precipitation of alpha phase on grain boundaries and get more uniform aged microstructure.

3.4 Improvement of Mechanical Properties by CWA

The heat-treatment method of aging after cold-working is known to promote uniform and fine precipitation of alpha phase remarkably in commercial beta titanium alloys¹⁵⁾. Therefore, in order to improve mechanical properties of the alloy Ti-13V-11Cr-3Al by suppressing preferential precipitation of alpha phase on grain boundaries, the effects of the heat-treatment of aging after cold-working on the ag-

Fig. 7 Longitudinal section of the central portion of the tensile specimen aged at 750 K for 200 ks and deformed just before break. Fig. 7 b) shows the high magnification observation of a microcrack shown in Fig. 7 a). Loading direction is vertical.

ing behavior and tensile properties were investigated.

Fig. 8 shows the variations of hardness of specimens aged at 750 K, 700 K, 650 K and 600 K after cold-working with 90% reduction. For the aging at 750 K, a decrease in the hardness appears after 360 ks. As for the aging at 700 K, 650 K and 600 K, the higher the aging temperature, the greater was the increase in the hardness. Compared with the variations of hardness in STA (Fig. 1), it is notable that cold-working accelerated the hardening response and increased the attained hardness in CWA at the same aging time and temperature.

Fig. 9 shows the variations of hardness in aging at 750 K as influenced by the reduction of cold-working. The larger the reduction of cold-working, the greater the hardness was at every aging time.

Fig. 10 shows the relation between ultimate tensile strength (σ_B) and reduction in area (RA) as influenced by reduction of cold-working (30%, 50% and 90%) and aging temperatures (700 K, 650 K and 600 K). The relation between ultimate strength and reduction in area obtained by STA is also shown in this figure. It is shown in this figure that CWA produced the better balance of strength and ductility than STA and, in CWA, higher reduction of cold-working and lower aging temperature are preferable for getting good balance of strength and ductility.

Fig. 11 shows the fracture surface (Fig. 11 a)) and the aged microstructure (Fig. 11 b)) of the specimen aged at 700 K for 100 ks after cold-working with 30% reduction. On the fracture surface, flat facets corresponding to grain boundary cracking were still observed. Compared with the aged microstructure in STA shown in Fig. 2, the precipitation of α phase became more uniform in the aged microstructure shown in Fig. 11 b), however, beta grain boundaries were distinguishable. In the fracture of the CWA specimen with 30% reduction of cold-working, grain boundary cracking is thought to function as a fracture mechanism. Therefore, in CWA, lower amount of cold-working before aging would produce inferior strength-duc-

Fig. 8 Variations of hardness of specimens aged at 750 K, 700 K, 650 K and 600 K after cold-working with 90% reduction.

Fig. 9 Variations of hardness aging at 750 K as influenced by the reduction of cold-working.

Fig. 10 Relation between ultimate tensile strength (σ_B) and reduction in area (RA) as influenced by reduction of cold-working (30%, 50% and 90%) and aging temperatures (700 K, 650 K and 600 K). The relation between ultimate strength and reduction in area obtained by STA is also shown in this figure.

tility balance to higher amount of cold-working. Concerning the effect of aging temperature in CWA, fine precipitates of alpha phase obtained by low temperature aging would be preferable to strength-ductility balance as shown in Fig. 10.

4. Conclusions

This research investigated the effects of aging after solution-treatment and aging after cold-working on the microstructure and mechanical properties of a commercial beta titanium alloy Ti-13V-11Cr-3Al.

The main findings can be summarized as follows:

In the aging after solution-treatment,

(1) Preferential alpha precipitation on beta grain boundaries was remarkable in the aged microstructure.

(2) With increase in aging time, strength increased, however, ductility decreased greatly due to the development of grain boundary cracking.

In the aging after cold-working,

(3) Cold-working before aging remarkably promoted aging response.

(4) Strength-ductility balance was improved greatly by this heat-treatment.

(5) The improvement was attained by suppressing preferential precipitation of alpha phase on grain boundaries and getting more uniform and finer aged microstructure.

(6) Higher reduction in cold-working and lower

Fig. 11 Fracture surface (Fig. 11 a)) and the microstructure (Fig. 11 b)) of the tensile specimen aged at 700 K for 20 ks after cold-working with 30% reduction.

temperatures in aging were preferable to the improvement.

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