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Duplex Aging of Ti-15V-3Cr-3Sn-3Al Alloy

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Abstract

Two-step as well as one-step aging treatments for Ti-15V-3Cr-3Sn-3Al specimens were performed to compare the mechanical properties between the two processes. In the case of specimens subjected to one-step aging for 8 h, the peak hardness was obtained for the 426^{o}C aged specimen. Regardless of the first aging temperature used in the two-step aging process, the second aging treatment at 426^{o}C/24 h would further increased hardness of the alloy but had different degrees. The presence of coarse and fine α precipitates in the β matrix accounted for increased hardness after duplex aging treatment. Some two-step aged specimens had high tensile strength (above 1400 MPa) but were accompanied by low ductility (less 3%) and high notch brittleness.

Keywords: Duplex aging; Ti-15V-3Cr-3Sn-3Al; Mechanical Property; Micro-structure

1. Introduction

Beta titanium alloys offer an attractive combination of strength, toughness and fatigue resistance in heavy sections. Among metastable β titanium alloys, Ti-15V-3Cr-3Sn-3Al (Ti-15-3) is one of the most widely used materials. Ti-15-3 can be manufactured into the ducting, clips, brackets and floor support structures as a replacement for Ti-6Al-4V alloy in the aircraft industry [1]. The superiority of Ti-15-3 alloy over Ti-6Al-4V is related to its better cold deformability in the solution-treated condition and higher strength after aging [2]. The tensile strength of Ti-15-3 alloy could be increased with an enhancement of α precipitation due to a decrease in β stability with increasing Al [3-4]. Increasing the aging temperature, a reduced volume fraction of α phase causes a decrease in strength of the Ti-15-3 alloy [5]. Aging over the temperature range of 400-750°C after solution treatment, α precipitation occurs first at β grain boundaries, followed by intragranular α precipitation [6]. Moreover, fine α precipitates are formed uniformly within β grains by nucleating at precursory isothermal ω particles while aging between 300-400°C [6].

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Refining the β grain is known to be an effective method to improve the ductility of the Ti-15-3 alloy, but has less influence on the tensile strength [7]. In addition, the notched tensile strength (NTS) decreases with increasing the β grain size of Ti-15-3 alloy [7]. Generally, the fracture toughness and ductility change in reverse manner with the tensile strength [5, 8]. In previous studies, the notched tensile specimens are used to evaluate the influence of microstructures on the notch brittleness of several titanium alloys and welds [9-12]. In this work, two-step as well as one-step aging treatments for Ti-15-3 specimens were performed to compare the mechanical properties between the two process routes. The results were then related to the inherent microstructures and fracture features of the Ti-15-3 alloy.

2. Experimental procedures

Ti-15-3 alloy in a sheet form with a thickness of 3.0 mm was used in this study. The chemical composition of the alloy in weight percent was 15.1 V, 3.05 Al, 2.92 Cr, 2.99 Sn, 0.071 Fe, 0.12 O, 0.016 C, 0.014 N and 0.021 S, with a balance of titanium. The as-received material was in the solution-annealed condition and had the β-transus temperature of about 760°C. The aging treatments were performed at the temperature range from 317 to 593°C for 8 h in vacuum, followed by argon-assisted cooling to room temperature. For the one-step aging treatment, the specimen was identified with a designation of the three-digital numbers (aging temperature in °C) prefixed with a capital letter A. In the case of the specimens subjected to the two-step aging treatment, a capital letter D was added in front the first aging temperature and the second aging temperature was kept at 426°C for 24 h. For example, the designation A482 represented that the specimen was directly aged at 482 for 8 h; the D538 specimen represented the specimen which was aged first at 538°C for 8 h then at 426°C for 24 h.

Mechanical tests such as tensile and notched tensile tests were carried out at room temperature. The ordinary tensile specimens were made according ASTM E8 standard and the double-edged notched specimens described elsewhere [14] were used. The tensile tests were conducted on a MTS machine at a strain rate of 6.67 x 10^{-4} s^{-1}, corresponding to a crosshead speed of 1 mm/min. The notched tensile tests were performed at a constant displacement rate of 1.0 mm/min. After testing, the macro-fracture appearance and fractographic examinations of various specimens were conducted using a Hitachi S4100 scanning electron microscope (SEM). For detailed microstructural observations, thin foil specimens were prepared by a standard jet-polisher and then examined with a transmission electron microscope (TEM).

3. Results and discussion

The as-received material in the solution-annealed condition consisted of equiaxed β grains without any observable precipitates (Fig. 1). In the D426 specimen, fine alpha needles were precipitated in the matrix (Fig. 2(a)). It was noted that the coarsening of α precipitates with decreasing in number and density of α needles became more significant in the D538 specimen (Fig. 2(b)). The as-received base material had the hardness of about Hv 274. After one-step aging treatment, the A317 and A371 specimens had the hardness of Hv281 and Hv304,respectively. In the one-step aged specimens, the A426 specimen reached the peak hardness value of Hv 428.

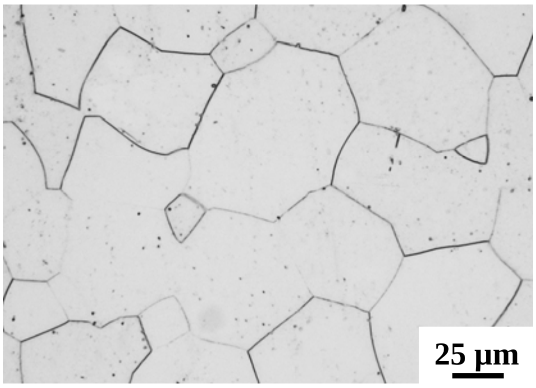

Fig. 1. Optical microstructure of the Ti-15-3 base material.

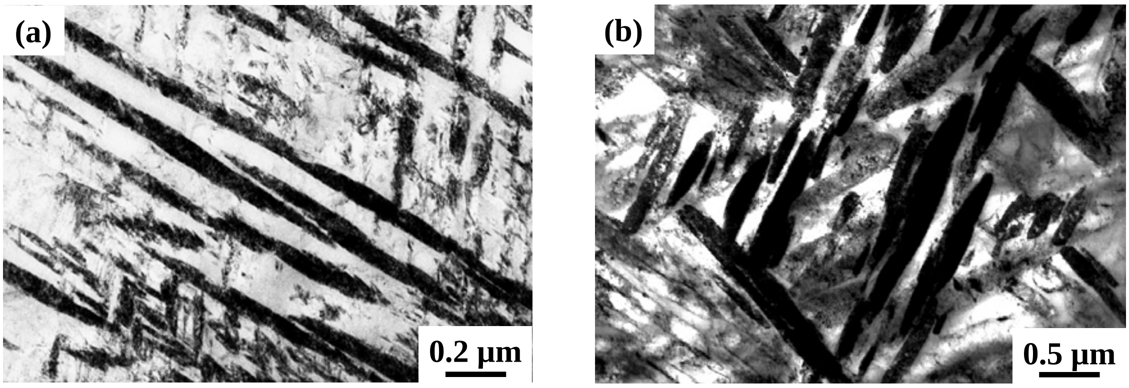

Fig. 2. TEM microstructure of the (a) D426 and (b) D538 specimens.

It has been reported that the small grain-sized Ti-15-3 specimens exhibit higher strength than the large grain-sized specimens in the solution-annealed condition [13]. Contrarily, the large grain-sized specimens have higher strength and better toughness than the small grain-sized specimens in the aged condition [13]. In previous studies, the fusion zone exhibited coarser grains and finer α precipitates relative to the base metal of Ti-15-3 welds [14]. Consequently, the higher hardness of the fusion zone than that of the base metal could be attributed to the effect of solution treatment during welding thermal cycles when the aging treatment was applied to the welds. With increasing the aging temperature higher than 482 °C (over-aging), coarsening of α caused an obvious decline in hardness of the aged specimens (Table 1). For the specimens underwent two-step aging treatment, the D317, D371 and D426 specimens possessed a similar hardness of about Hv 460. This implied that the second aging treatment at 426 °C/ 24h was expected to produce ample α precipitates to cause remarkable hardening for those specimens having the first aging temperature lower than 426°C. The hardness of the D538 and D593 specimens was lower than the hardness of the D317, D371, and D426 specimens. A more complete precipitation of fine α structure resulted in an increased hardness of the D317, D371 and D426 specimens. In contrast, the formation of coarse α precipitates in the first aging treatment of the D538 and D593 specimens was due to over-aging, leading to little or no further precipitation of α in the second aging treatment.

Table 1. Aging temperature and hardness relationship of theTi-15-3 specimens.

Aging Temperature (℃)	Hardness (Hv)	
	1-Step Aging	2-Step Aging
317	281	463
371	304	455
426	428	461
482	395	438
538	376	383
593	343	347
648	290	338

Table 2. lists the typical tensile properties as well as notched tensile strength of various specimens. The results indicated that specimens with high hardness (> Hv 450) also possessed significantly high ultimate tensile strength (about 1400 MPa) but considerably low ductility (<5%). The ultimate tensile strength / elongation of the D538 and D593 specimens were about 1200 MPa / 10% and 1100 MPa / 16%, respectively. It clearly demonstrated that a decreased strength was accompanied with an improved ductility. It was noticed that the notched tensile strength (NTS) of the specimens increased with increasing the ductility. The D593 specimen possessed the highest ductility in ordinary tensile test and NTS in notched tensile test among the other two-step aging specimens.

Table 2. Mechanical properties of two-step aged specimens.

Specimen	Ordinary Tensile			Notched Tensile
	UTS (MPa)	Yield (MPa)	Elongation (%)	NTS (MPa)
D-426	1400	1337	2	886
D-538	1247	1139	10	1239
D-593	1115	1005	16	1325

Figure 3 displays the macroscopic fracture appearance of several notched tensile specimens. The D317, D371 and D426 specimens had low NTS (high notch brittleness) and exhibited wide flat fracture regions (Fig. 3(a)). For the D538 and D593 specimens with high NTS, an extensive shear fracture and ductile feature was observed (Fig. 3(b)). Figure 4 contains SEM fractographs of some specimens after notched tensile tests. These specimens with low NTS displayed cleavage-like fracture mixed with shallow dimple after notched tensile tests (Fig. 4(a)). Moreover, the extent of cleavage-like fracture reduced but dimple fracture increased for the specimens with low notch brittleness or high NTS (Fig. 4(b)). The coarse α phase in the over-aged

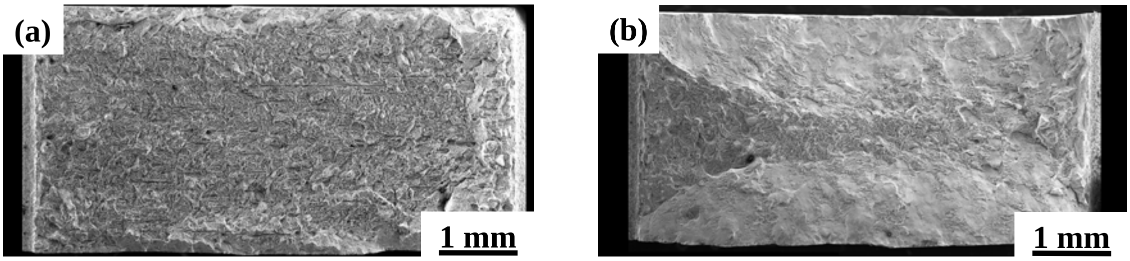

Fig. 3. Notched tensile fracture of the (a) D426 and (b) D538 specimens

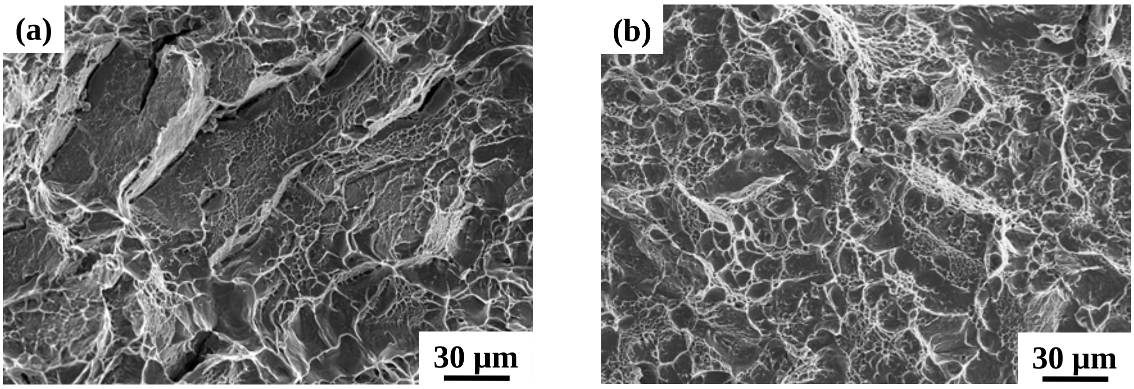

Fig. 4. SEM fractographs of the (a) D426 and (b) D538 specimens

specimens was responsible for the formation of large dimples. Furthermore, intergranular fracture and grain boundary shear were found for the D648 specimen, resulting in a reduced NTS and ductility.

Summary

Regardless of the first aging temperature used in the two-step aging process, the second aging treatment at 426 ℃/24 h would further increase hardness of the Ti-15-3 alloy but had different degrees. The limited amount of α precipitates during the second step aging (426 ℃/24h) caused a minor increase in hardness of the D538 and D593 specimens. The low ductility of the D317, D371 and D426 specimens was responsible for the high notch brittleness or low NTS of the material.

Acknowledgements

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