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Materials Letters 62 (2008) 1114–1117
materials letters
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Notched tensile strength of SP-700 laser welds

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Received 17 April 2007; accepted 31 July 2007
Available online 7 August 2007

Abstract

Notched tensile tests were performed to evaluate the influence of post-weld heat treatments (PWHTs) on the notched tensile strength (NTS) of two α+β titanium alloy welds. The results indicated that SP-700 laser welds were notch brittle unless a high PWHT temperature, e.g. 760 °C, was applied. The lowest NTS was associated with the peak-aged weld, which was aged at 482 °C for 1 h. In contrast, Ti-6Al-4V welds did not exhibit notch sensitivity in the as-welded or in the PWHT conditions. The reduced plasticity due to the strengthening of fine α in the β matrix account for the observed notch brittleness of the SP-700 laser welds. Increasing the PWHT temperature associated with coarsening the α+β structure reduced the notch sensitivity of SP-700 laser welds.

Keywords: Notched tensile strength; Laser welding; Ti-4.5Al-3V-2Mo-2Fe; Ti-6Al-4V

1. Introduction

SP-700, an α+β titanium alloy with a nominal chemical composition (wt.%) of Ti-4.5Al-3V-2Fe-2Mo, is designed to improve superplastic formability and lower the operating temperature as compared to Ti-6A1-4V alloy [1]. SP-700 exhibits superplasticity at about 700 °C, whereas the conventional Ti-6A1-4V shows superplasticity at approximately 900 °C [2,3]. As a result, the production cost of SP-700 alloy can be reduced significantly by lowering the operation temperature. In addition, SP-700 alloy offers several advantages over Ti-6A1-4V including higher hardenability, faster age-hardening response, and superior mechanical properties [2–6].

Laser welding is a mature technology and has become of great interest in various industries for precision welds. Nowadays, laser welding is used extensively owing to the ease of automation and improved product quality [7,8]. In the open literatures, rather few works have studied the mechanical properties of titanium welds, in particular this SP-700 alloy. This study focused on the notched tensile strength (NTS) of SP-700 laser welds which were post-weld heat-treated at various temperatures. The NTS results and the microstructures of the welded SP-700 specimens were also compared to those of Ti-6A1-4V welds.

2. Material and experimental procedures

Two α+β titanium alloy sheets, were used in this investigation: SP-700 (3.4 mm), with an alloy composition (wt.%) of 4.70 Al; 2.45 V; 2.15 Fe and 1.82 Mo; and Ti-6Al-4V

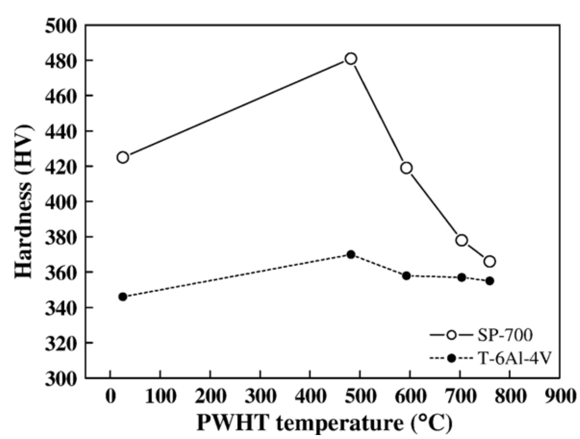

Fig. 1. Micro-hardness in the weld metal of SP-700 and Ti-6Al-4V welds at various post-weld heat treatment (PWHT) temperatures.

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doi:10.1016/j.matlet.2007.07.059

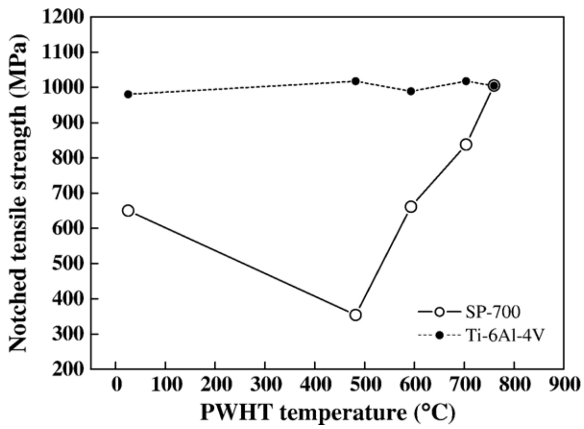

Fig. 2. The influence of post-weld heat treatment (PWHT) temperatures on the notched tensile strength (NTS) of laser welds.

(4.0 mm) with 6.20 Al; 4.22 V and 0.14 Fe. The microstructure of as-received SP-700 and Ti-6Al-4V sheets in the mill-annealed condition consisted of β distributed in the elongated α-grain boundaries. The major difference between these two alloys was that SP-700 contained more β than Ti-6Al-4V. The micro-hardness of the as-received alloys was approximately HV 340 for SP-700 and HV 360 for Ti-6Al-4V. Tensile properties of the two mill-annealed alloys were similar, and typically had an ultimate tensile strength of 970 MPa, yield strength of 940 MPa and 18% elongation. The materials exhibited a low anisotropy with respect to the rolling direction.

All specimens were welded in the mill-annealed condition with the welding direction normal to the rolling direction. A Rofin-Sinar RS 850 CO_2 laser was utilized for bead-on-plate welding of titanium specimens in one pass. The processing parameters (laser power and travel speed) were 2.7 kW and 1000 mm/min for SP-700, but 3.2 kW and 800 mm/min for Ti-6Al-4V. The accuracy of the moving table was within ±0.1 mm/min for the specified travel speeds. Post-weld heat treatments (PWHTs) were performed on the welds in the temperature range of 482–760 °C (900–1400 °F) for 1 h under vacuum, followed by Ar-assisted cooling to room temperature. Double-edge notch specimens with the notches located at the weld metal, which were ground smooth prior to tests, were used in this study [9]. Notched tensile tests were performed in air at a constant displacement rate of 1.0 mm/min and the results were the average of at least three specimens for each testing condition. The dependence of PWHT temperatures on the NTS of laser welds was evaluated. In addition, the correlation between microstructures and the fracture characteristics of notched tensile specimens was examined.

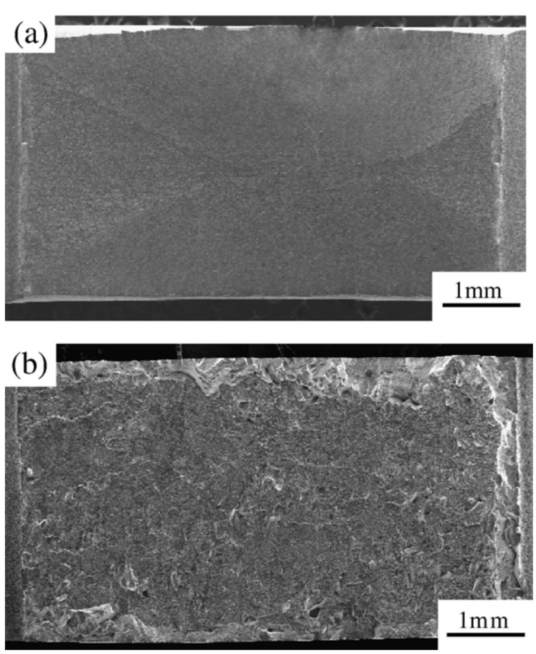

Fig. 3. Macroscopic fracture appearance of SP-700 specimens after notched tensile tests: (a) mill-annealed material; and (b) 482 °C-aged weld.

3. Results and discussion

Fig. 1 shows the variation of micro-hardness with PWHT temperatures in the weld metal of the SP-700 and Ti-6Al-4V laser welds. The results indicated that the weld metal of SP-700 alloy was

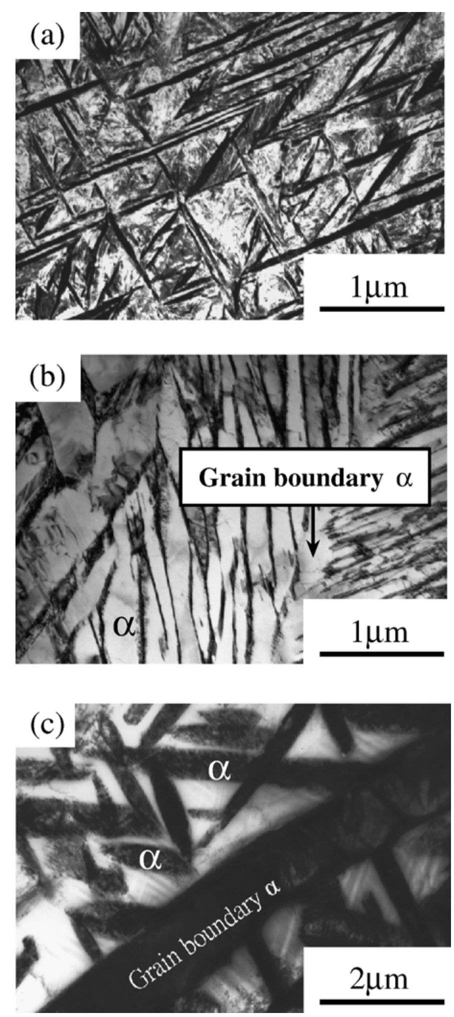

Fig. 4. TEM photographs showing the microstructures in the weld metal: (a) as-welded SP-700; (b) as-welded Ti-6Al-4V; and (c) 760 °C-aged SP-700 specimens.

considerably harder than that of Ti-6Al-4V in the as-welded condition. The peak hardness of SP-700 welds could reach HV 480 after aging at 482 °C/1 h. PWHTs at higher temperatures lead to an obvious decline in hardness of the welds as shown in Fig. 1. In contrast, Ti-6Al-4 V welds exhibited a sluggish response to PWHTs for temperatures up to 760 °C. Since both titanium alloys were received in the mill-annealed condition, they were reluctant to change hardness after PWHTs. It was noted that a narrow heat-affected zone (HAZ) of less than 1 mm with hardness in between the weld metal and the base metal was observed for all welded specimens, regardless of the PWHTs. For instance, the hardness of the HAZ of the as-welded SP-700 specimen was in the range of 350–400 HV, which was in between the weld metal (425 HV) and the base metal (340 HV).

Fig. 2 shows the NTS results of various specimens tested in laboratory air. The NTS of mill-annealed SP-700 and Ti-6Al-4V alloys was 1100 and 1020 MPa, respectively. In the as-welded and aged conditions, Ti-6Al-4V welds had a NTS level similar to that of the mill-annealed material. This was consistent with minor changes in hardness of the Ti-6Al-4V welds with distinct PWHTs. Although the mill-annealed SP-700 alloy had a slightly higher NTS than Ti-6Al-4V (1100 vs. 1020 MPa), surprisingly the SP-700 welds had a considerable drop in NTS for specimens aged below 704 °C. The lowest NTS was associated with the weld aged to its peak hardness, i.e., the 482 °C-aged weld. It has been suggested that stress-relieving temperature range is 538–593 °C (1000–1100°F) for Ti-6Al-4 V welds [10]. However, if the same temperature range were employed to perform the stress relief of SP-700 welds, notch brittleness of the weld metal would result. It was obvious that an improper PWHT of SP-700 welds might lead to deterioration of the mechanical properties of the welds. As a result, the recommended PWHT temperature for the SP-700 welds was in the neighborhood of 760 °C to obtain a NTS level of approximately 1000 MPa. Further improvement of NTS to 1100 MPa could be achieved by PWHT of SP-700 welds at 815 °C with the aid of a suitable fixture to avoid excessive distortion for practical applications.

Fig. 3 shows the typically macroscopic fracture appearance of some specimens after notched tensile tests. The fracture surface of the mill-annealed SP-700 specimen consists of flat fracture (FF) and slant fracture (SF) regions as shown in Fig. 3(a), in which the reduction of thickness before its final fracture is noticeable. The same trend was observed in the mill-annealed Ti-6Al-4V alloy, indicating that both alloys possessed high plasticity and underwent notch-blunting before rupture. On the other hand, the fracture surface of notch brittle specimens, which included as-welded, 482 °C- and 593 °C-aged SP-700 welds, revealed only flat fracture and very limited thickness reductions (Fig. 3(b)). The severity of the notch brittleness was reduced as the aging temperature raised above 704 °C. In contrast, all Ti-6Al-4V welds exhibited a fracture surface similar to that shown in Fig. 3(a), indicating that they had a better plasticity and greater resistance to notch brittleness as compared to the SP-700 welds. In general, plane stress state is associated with high toughness and SF, while plane strain state is accompanied by low toughness and FF [11]. The presence of a mixed fracture appearance (Fig. 3(a)) would reflect an intermediate toughness condition [11] and produce a tougher failure as compared to that of entirely FF (Fig. 3(b)).

Fig. 4 reveals the TEM microstructures of the weld metal of several laser-welded specimens. The weld metal of SP-700 in the as-welded condition was composed of coarse acicular α, in addition to fine acicular α in the β matrix (Fig. 4(a)). The as-welded microstructure of the SP-700 weld was considerably finer than that of the Ti-6Al-4V weld (Fig. 4(b)). It should be noted that the movement of dislocations is impeded by the refined $\alpha+\beta$ structure, resulting in less deformation (or notch-blunting) and higher hardness in the as-welded SP-700 specimen. The decomposition of retained β during PWHT further increased the hardness of the 482 °C-aged specimens [4]. For SP-700 welds aged at 760 °C, a significant coarsening of $\alpha+\beta$ structures resulted, along with the formation of continuous α films at grain boundaries (Fig. 4(c)).

Fig. 5 shows the fracture appearance of the notched tensile specimens. As the amount of grain boundary α increased with rising the PWHT temperature, the tendency to form intergranular ductile fractures likewise increased, as shown in Fig. 5(a) and (b).With little or no grain boundary α in the specimens, as found in as-welded and

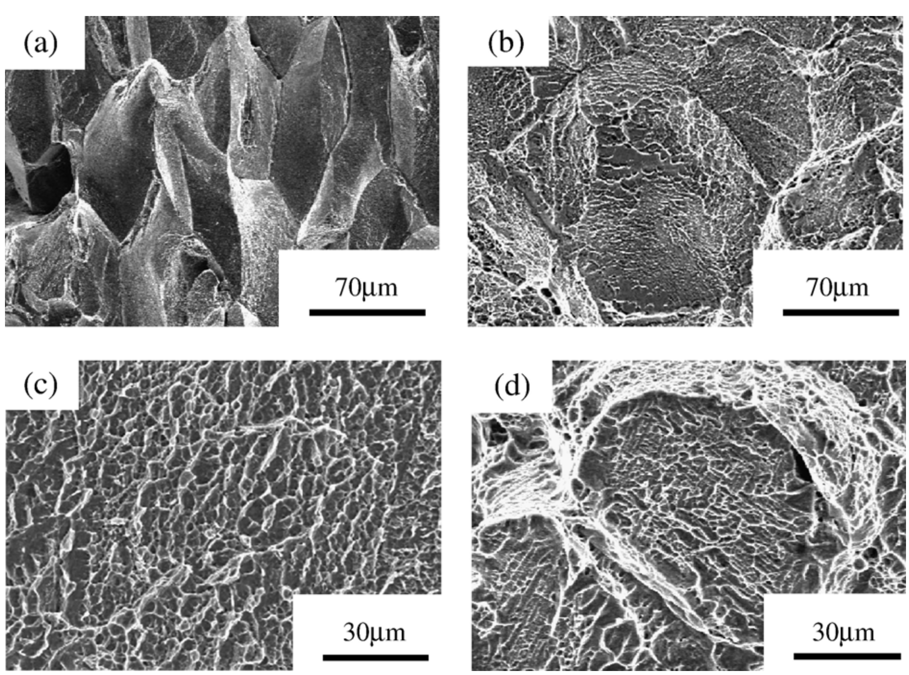

Fig. 5. SEM photographs showing the typical fracture appearance of titanium welds: (a) 593 °C-aged SP-700; (b) 760 °C-aged SP-700; (c) 482 °C-aged SP-700; and (d) 482 °C-aged Ti-6Al-4V specimens.

482 °C-aged SP-700 specimens, a transgranular fracture with fine dimples was the typical fracture mode (Fig. 5(c)). In contrast to the peak-aged Ti-6Al-4V weld (more α at grain boundaries as well as in the matrix), a transgranular fracture with dimples outlining the grain boundary was clearly seen in Fig. 5(d).

4. Conclusions

SP-700 laser welds exhibited notch brittleness at various degrees depending on the post-weld heat treatment (PWHT) temperature. The lowest notched tensile strength (NTS) was associated with the peak-aged weld. Unless a high PWHT temperature (e.g. 760 °C) was employed, SP-700 laser welds could not achieve an NTS level of 1000 MPa. In contrast, Ti-6Al-4V welds did not show notch brittle behavior in the as-welded or aged conditions. The presence of a refined α in the β matrix reduced the plasticity of the weld metal, leading to notch brittleness of SP-700 laser welds. Coarsening the α + β structure by increasing the PWHT temperature lowered the notch sensitivity of SP-700 laser welds.

Acknowledgements

The authors gratefully acknowledge the financial support of this study by the National Science Council of Republic China (NSC 94-2216-E-019-006).

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