Notched Tensile Fracture of Ti–6Al–4V Laser Welds at Elevated Temperatures

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Notched tensile tests of Ti–6Al–4V laser welds that were subjected to post-weld heat treatments (PWHTs) at 482 and 704°C were carried out in air at temperatures from 25 to 450°C. The experimental results were also compared with those of the mill-annealed base metal (MB) specimens tested at similar temperatures. Generally, the notched tensile strength (NTS) of the specimens was sensitive to the test temperature. The NTS of laser welds was lower than that of the MB specimen at room temperature, but the trend reversed at 450°C. The presence of thick grain boundary α layers, which promoted intergranular fracture at elevated temperatures, could account for the lowered NTS of the weld after PWHT at 704°C.

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1. Introduction

Titanium alloys are extensively used in the aerospace, marine and chemical industries because of their remarkable strength-to-weight ratio and excellent corrosion resistance in distinct environments. Diphase α + β titanium alloys can be heat-treated to achieve various mechanical properties for diverse applications.1) The microstructures of α + β titanium alloys play an important role in determining the mechanical properties and fracture behavior of these materials.2) Ti–6Al–4V, an α + β alloy, is by far the most widely used titanium alloy, accounting for at least half of total titanium consumption. It has been reported that a coarse acicular α structure leads to higher fracture toughness but with considerably lower tensile ductility than the equiaxed structure in Ti–6Al–4V and Ti–6Al–6V–2Sn alloys.3) Heat treatment of Ti–6Al–4V in the α + β field results in increased toughness with a slight decrease in ductility and strength in comparison with the mill-annealed material.4)

It has also been reported that the fusion zone (FZ) of the as-welded Ti–6Al–4V weld has low ductility as a result of a fine acicular microstructure and a large prior β grain size.5) The FZ ductility of a Ti–6Al–4V weld can be improved after post-weld heat treatments (PWHTs) at 700 to 900°C.6) Interestingly, the fracture toughness of the FZ in the as-welded and heat-treated conditions is higher than that of the mill-annealed base metal.7) Moreover, the fatigue crack growth rate resistance of the fusion zone of a Ti–6Al–4V weld is superior to that of the base metal (BM).8) Regarding the welding processes, tungsten inert gas arc welding and electron beam welding are traditionally methods for joining components and/or piping systems made of titanium alloys.9) For precision and high-quality welds, laser beam welding has proven to be cost effective and can produce a weld of quality similar to that of electron beam welding.9)

Previous studies of SP-700 (Ti–4.5Al–3V–2Mo–2Fe)10,11 and Ti–6Al–6V–2Sn12 laser welds indicated that the high notch sensitivity of these welds at room temperature was resulted unless a suitable PWHT at higher temperatures was performed on the welds. In addition, the high notch sensitivity of such high-strength titanium laser welds can be reduced by preheating prior to welding.13,14) In the case of the Ti–4.5Al–3V–2Mo–2Fe weld after PWHT at 704°C, the formation of grain boundary α layers, which promote grain boundary shear, is believed to decrease the notch sensitivity of the weld at room temperature.10,13)

As a general rule, the applications of titanium alloys are restricted to temperatures below 550°C. The upholding of a high notched tensile strength (NTS) is necessary to avoid premature cracking/failure in service. This study investigated the effect of test temperature on the NTS of Ti–6Al–4V laser welds. The results were compared with those of mill-annealed Ti–6Al–4V specimens and Ti–6Al–6V–2Sn welds.12,14) The decrease in NTS and the change in fracture characteristics of the specimens with temperature were also correlated with the fracture features.

2. Material and Experimental Procedures

Ti–6Al–4V alloy with a thickness of 3.0 mm in the mill-annealed condition was used in the experiment. The chemical composition in weight percent of the alloy was 5.90 Al, 3.95 V, 0.11 Fe, 0.01 C, 0.07 O, 0.01 N and a balance of Ti. The Aleq and Moeq15 of this alloy were calculated to be approximately 6.0 and 2.9, respectively. The tensile properties of the mill-annealed base metal (MB) specimen include an ultimate tensile strength of 962 MPa, yield strength of 830 MPa and elongation of 17%. A CO2 laser was utilized for bead-on-plate welding in keyhole mode in one pass at room temperature. A copper mirror with a focal length of 200 mm was utilized, and the focal point of the laser beam was positioned at 0.5 mm below the specimen surface. Besides, a helium jet was used to blow the plasma plume away and argon was used as the tail-shielding and back-shielding gas to prevent oxidation at high temperatures. The welding parameters included a laser power of 3.1 kW and a travel speed of 800 mm/min. All the specimens were welded in the mill-annealed condition with the welding direction normal to the rolling direction. The welded specimen in the as-welded condition was named the AW specimen. PWHTs were
performed on some of laser welds at 482 and 704°C for 3 h in vacuum, followed by argon-assisted cooling to room temperature. These specimens were designated as the W-482 and W-704 specimens, respectively.

Micro Vickers hardness tester was employed to measure the hardness in distinct regions of a weld under a load of 300 g. Double-edge notched specimens11,12) with a sharp notch tip radius of approximately 100 µm were made by an electro-discharge wire cutter. For the welded specimens, the notches were located at the center of the FZ to ensure crack growth along the weld centerline as much as possible during tensile loading. Notched tensile tests were carried out in air at a constant displacement rate of 1.0 mm/min. For high-temperature tests, the specimens were placed in a furnace and heated to the predetermined temperature (150, 300 and 450°C), then held at that temperature for 30 min before testing. The NTS results were presented as the average of at least three specimens for each testing condition. The fracture surfaces of distinct specimens were examined using a scanning electron microscope (SEM), with attention paid to the change in fracture features. 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

3.1 Microstructure observation and microhardness measurements

Figure 1(a) shows a typical cross-section of the weld and its microstructures, in which the fusion zone (FZ) and the heat-affected zone (HAZ) are narrow due to the low energy input of the laser welding process. Owing to the high cooling rate of laser welding, the FZ of the AW specimen consisted of coarse columnar grains with fine, needle-like structures in the matrix under optical microscopy (Fig. 1(b)). Additionally, the coarse-grained HAZ exhibited similar microstructures to the FZ of the weld. At higher magnification, a thin layer of α was observed to decorate the grain boundaries in the FZ (Fig. 1(c)) and the coarse-grained HAZ of the AW specimen. Increasing the PWHT temperature caused coarsening of the grain boundary α as well as α platelets in the grain interior of the welds.

The variation in microhardness across the FZ of various welds in the as-welded and PWHT conditions is shown in Fig. 2. In the as-welded condition, the microhardness in the FZ of the Ti–6Al–4V weld was about Hv 361, which was higher than that of the base metal (BM) of Hv 334. PWHT at 482°C resulted in a slight increase in FZ hardness to Hv 372. A moderate decrease in the FZ hardness to Hv 356 was obtained for the weld with the PWHT at 704°C. Normally, the HAZ hardness was slightly lower than the FZ hardness at a given PWHT temperature. The results also indicated that the hardness of the BM was lower than that of other regions in a weld, regardless of the PWHT conditions. In a previous study, the Ti–6Al–6V–2Sn alloy with Al\text{eq} of 6.2 and Mo\text{eq} of 4.8 shows noticeable hardening after welding.12) In the as-welded condition, the FZ hardness of Ti–6Al–6V–2Sn alloy could be as high as Hv 440.12) The peak hardness of the Ti–6Al–6V–2Sn laser weld reached Hv 460 after PWHT at 482°C.12) The hardness response of different Al\text{eq} and Mo\text{eq} between Ti–6Al–6V–2Sn and Ti–6Al–4V welds is discussed later in the text.
Figure 3 shows TEM micrographs of the FZ in Ti–6Al–4V welds with different PWHT conditions. In the as-welded condition, fine interlocked α in the matrix, grain boundary α films along with few retained β were observed (Fig. 3(a)). It was noted that α laths in the FZ of the Ti–6Al–4V weld were coarser than those of the Ti–6Al–6V–2Sn weld in the as-welded condition, resulting in a lower FZ hardness in the former. For instance, the FZ hardness of Ti–6Al–4V and Ti–6Al–6V–2Sn welds was Hv 361 and 440, respectively. It is known that α + β titanium alloys with higher Moₑq possess higher hardenability and facilitate the formation of finer acicular α in the FZ after laser welding. Therefore, the finer acicular α + β microstructures were responsible for the higher FZ hardness in the as-welded condition. A previous study of SP-700 laser welds also showed similarly high FZ hardness in comparison with Ti–6Al–4V welds. Furthermore, the high cooling rate in the FZ during laser welding also expected to assist the formation of thin β plates. In the W-482 specimen, such thin plates were decomposed into small α and β islands (Fig. 3(b)), leading to a slightly higher hardness than the AW specimen. This is a phenomenon related to precipitation hardening resulting from the precipitation of fine α particles. Increasing the PWHT temperature to 704°C, coarse lamellar structures consisting of α and β were observed (Fig. 3(c)), which could be responsible for the decrease in the hardness of the W-704 specimen. It is obvious that the microstructures in the FZ and HAZ are different from those in the BM (mill-annealed) of the welded specimens. The MB specimen, in fact, consists of a low percentage of β at the boundaries of elongated α grains, as shown in Fig. 3(d).

3.2 Notched tensile tests

Figure 4 shows the results of the notched tensile tests at room temperature and 450°C. The NTS of the MB specimen (1210 MPa) was obviously higher than its ultimate tensile strength (962 MPa) at room temperature. As shown in Fig. 4(a), the NTS and ductility of all welded specimens were noticeably lower than those of the MB specimen at room temperature. However, slightly improved ductility and NTS at room temperature could be obtained for the W-704 specimen. In contrast to the room temperature behavior, the MB specimen exhibited a remarkable drop in NTS and a great improvement in ductility at 450°C, as illustrated in Fig. 4(b). Moreover, the W-704 specimen also displayed a slight decrease in NTS and an improved ductility at 450°C. In the case of the AW and W-482 specimens tested at 450°C, a marginal decrease in NTS and a moderate increase in ductility were observed. It was possible that the lack of deformation compatibility between the α and β phases
resulted in the low NTS of the MB specimen at 450°C. On the contrary, the fine acicular structures in the form of basket-weave in the AW and W-482 specimens were less likely to form interfacial separations and responsible for the higher NTS at elevated temperatures. Furthermore, the improved ductility for the AW and W-482 specimens at 450°C might cause strain-hardening and persist in higher NTS at elevated temperatures.

The results of the notched tensile tests of distinct specimens at different temperatures are shown in Fig. 5. The MB specimens exhibited a rapid decline in NTS with increasing test temperature. These specimens had the highest NTS at room temperature and the lowest NTS at 450°C for both Ti–6Al–4V and Ti–6Al–6V–2Sn alloys. At room temperature, the W-704 specimen had a slightly higher NTS than the AW and W-482 specimens, but a reverse trend was found for similar specimens at 450°C. In general, all of the welds had a tendency of decreasing NTS with increasing test temperature, except for the AW specimen which showed lower notch sensitivity at room temperature. When the test temperature was raised to 450°C, the Ti–6Al–6V–2Sn welds exhibited no beneficial effect on the NTS relative to the Ti–6Al–4V welds, which could be related to the difference in fracture behavior as discussed in the next section.

### 3.3 SEM Fractography

Figure 6 displays the macro-fracture appearance of the specimens tested both at room temperature and 450°C. The MB specimen showed an obvious increase in thickness reduction with increasing the test temperature (Fig. 6(a)). This result implies the enhanced deformability of the MB specimen at elevated temperatures. For laser welds, the notched fracture appearance was much rougher and more irregular as compared to the MB specimen. Upon examining the macro-fracture morphology of the welds tested at room temperature, all the welds comprised of a certain extent of shear fracture region. Such observation reflected that the welds underwent predominantly ductile fracture during the notched tensile tests regardless of the test temperature. It seemed that the high NTS of the W-704 specimen could be associated with an improved ductility (Fig. 6(b)) relative to the AW and W-482 specimens at room temperature (Fig. 6(c)). Similar to the MB specimen, an increase in the test temperature resulted in the increased ductility of the welds, particularly for the welds tested at 450°C (Fig. 6(d)). At elevated temperatures, the higher NTS of the AW and W-482 specimens could be attributed to a fine acicular structure. In contrast, the lower NTS of the MB specimen was associated with the banded $\alpha + \beta$ structure.

Figure 7 shows SEM fractographs revealing the typical fracture appearance of various specimens. The MB specimen had extensive transgranular dimple fractures at room temperature and an enlarged dimple size at 450°C. For the AW and W-482 specimens fractured at room temperature, transgranular dimples mixed with cleavage-like fractures on certain grains were observed (Fig. 7(a)). For those grains showing cleavage-like fractures, lath features on the fracture surface could be related to $\alpha + \beta$ microstructures in the basket-weave form. It has been reported that dimple fracture prevails under low triaxiality, whereas, cleavage fracture is dominant under high triaxiality in the fracture separation of
the Ti–6Al–4V alloy. Cleavage fracture in the FZ of Ti–6Al–4V welds could be the results of the combined effect of a sharp notch and the coarse-grained structure during the notched tensile tests. In addition, the presence of weak grain boundary α layer resulted in the occurrence of grain boundary shear in the AW and W-482 specimens during straining, as shown in Fig. 7(a). Moreover, an increased likelihood of intergranular fracture in the W-704 specimen could be attributed to the presence of thicker grain boundary α layers (Fig. 7(b)). With increasing test temperature, an improved ductility of all welds led to a decreased trend of cleavage-like fracture. At 450°C, transgranular coarse dimples mixed with an increased extent of shear at the columnar boundaries were found in the AW and W-482 specimens (Fig. 7(c)). Such event was associated with the improved ductility, i.e., reduced cleavage-like fracture, and activated grain boundary shear of welded specimens at elevated temperatures. For the W-704 specimen tested at 450°C, a significant increase in the intergranular fracture along columnar boundaries together with transgranular coarse dimples was found (Fig. 7(d)). An

Fig. 6 The macro-fracture appearance of (a) the MB specimen at 450°C, (b) the W-704 specimen at room temperature, (c) the W-482 specimen at room temperature, (d) the W-482 specimen at 450°C.

Fig. 7 SEM fractographs of (a) the AW (left) and W-482 (right) specimens at room temperature, (b) the W-704 specimen at room temperature, (c) the AW (left) and W-482 (right) specimens at 450°C and (d) the W-704 specimen at 450°C.
increased extent of the intergranular separation at elevated temperatures was attributed to the formation of relatively thick grain boundary in the W-704 specimen. It also confirmed that the grain boundaries were relatively weaker than the grain interiors of the specimens. The presence of thick grain boundary layer also accounted for the inferior NTS of the W-704 specimen compare to the AW and W-482 specimens at elevated temperatures.

4. Summary

The influence of test temperature on the NTS of Ti–6Al–4V laser welds that were subjected to various PWHTs was investigated. The results indicated the hardness of the BM was lower than that of other regions in a given weld regardless of the PWHT conditions. The precipitation of fine α islands within thin β plates might account for a slight hardening in the W-482 specimen as compared to other welds. Coarse plate-like and intergranular α were responsible for a lowered hardness of the W-704 specimen. All the Ti–6Al–4V laser welds exhibited low notch sensitivity at room temperature and a trend of decreasing NTS with increasing test temperature, especially for the MB and W-704 specimens. Among the welds, the W-704 specimen had a slightly higher NTS than the AW and W-482 specimens at room temperature, but this trend reversed at 450°C. With the presence of sharp notches, the cleavage-like fracture on certain grains mixed with grain boundary separations was observed on the tensile fracture surfaces of all the welds. Upon increase the test temperature, cleavage-like fracture was less likely to be observed. At 450°C, a significant increase in intergranular fracture along columnar boundaries accounted for the inferior NTS of the W-704 specimen compared to the AW and W-482 specimens. In contrast, tear fracture at the columnar boundaries of the latter, which could be partly attributed to the reduced difference in strength between the grain interiors and boundaries, resulting in the higher NTS of the AW and W-482 specimens at elevated temperatures.

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