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Microstructure and notched tensile fracture of Ti–6Al–4V to Ti–4.5Al–3V–2Fe–2Mo dissimilar welds

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ABSTRACT

Dissimilar welding of Ti–6Al–4V (Ti-6-4) to Ti–4.5A1–3V–2Fe–2Mo (SP-700) alloys was performed using a CO_2 laser. The microstructure and notched tensile strength (NTS) of the dissimilar welds were investigated in the as-welded and post-weld heat treatment (PWHT) conditions. Moreover, the results were compared with homogeneous laser welds with the same PWHT. The dilution of SP-700 with the Ti-6-4 alloy caused the formation of fine needle-like α + β structures, resulting in the exhibition of a moderately high fusion zone (FZ) hardness of HV 398. The high FZ hardness (HV 438) for the weld with the PWHT at 482 °C was associated with low NTS or high notch brittleness. The fracture appearance of the notched tensile specimen was related to its inherent microstructure. With increasing the PWHT temperature, the thickness of grain boundary α increased, which promoted an intergranular dimple fracture. By contrast, fine shallow dimples were present in the peak-aged weld, which was induced by the refined α + β microstructures in the basket-weave form.

1. Introduction

Of all α + β titanium alloys, Ti–6Al–4V alloy is the most widely used; however, its poor workability and heat treatability limits its usage in certain fields. The Ti–4.5Al–3V–2Fe–2Mo is a β-rich α + β titanium alloy, which is also known as SP-700, based on its excellent superplasticity at 700 °C [1]. This alloy has several advantages over Ti–6A1–4V, such as heat-treatability, cold bendability and superior mechanical properties [2–4]. A wide range of strength (up to 1400 MPa) can be obtained through the appropriate heat treatment of SP-700 [5]. In addition, SP-700 demonstrates a faster response to age-hardening than other heat-treatable titanium alloys after solution treatment [6]. The higher strength and finer structure account for the superior fatigue strength of SP-700 compared with Ti–6A1–4V [2]. The high toughness of SP-700, which contains coarsened acicular α or plate-like α, is the result of increased micro-cracking and crack-branching of the alloy [7,8]. Increasing the prior β grain size and coarsening the acicular α improve the fracture toughness of SP-700 [9].

Joining of components by welding processes is often unavoidable for the assemblage of individual component. Laser beam welding can offer the flexibility to weld all light metals and their combinations [10]. Traditionally, gas tungsten arc [11,12] electron beam [13,14] welding processes are used for the welding of Ti–6Al–4V. Laser beam can be superior to other welding processes in welding titanium alloys. For the welding of pure Ti, laser beam welding has a narrower weld-seam, less deformation and finer grains than the gas tungsten arc and electron beam welding processes [15]. Recently, the laser beam has been used successfully to weld a newly developed titanium alloys [16]. In the welding of Ti–6A1–4V, the laser beam weld exhibits a higher fatigue crack growth resistance than the electron beam and gas tungsten arc welds [17]. In a previous study, filler metal was added to alter the fusion zone composition/microstructure of the Ti-6-4 electron beam weld [18]. To reduce material expense or increase propensity, the assemblage of components that consist of different alloys by using the laser welding process is of technological interest for industrial applications. A sound weld between Nb and Ti–6Al–4V has been made by the laser beam welding process [19]. However, only limited studies have investigated the microstructures and mechanical properties of dissimilar titanium welds [20,21].

The presence of notches or stress concentrations can deteriorate the mechanical properties of a material. The introduction of sharp notches into a specimen has been used to evaluate the effect of microstructures on the notch brittleness of the SP-700 alloy and weld [22–25]. In contrast to Ti–6Al–4V [26], SP-700 laser welds are highly susceptible to notch brittleness [23]. Only appropriate

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post-weld heat treatment (PWHT) can lower the notch brittleness of SP-700 laser welds [23]. This study evaluated the NTS of Ti–6Al–4V (Ti-6-4) to Ti–4.5Al–3V–2Fe–2Mo (SP-700) dissimilar laser welds with distinct PWHTs. The relationship between microstructural features and fracture characteristics of various specimens was investigated.

2. Materials and experimental procedures

The chemical composition of the 3.0 mm thick plate of Ti–6A1–4V (Ti-6-4) alloy, by weight percent, is 5.90 Al, 3.95V, 0.11 Fe, 0.01 C, 0.07 O, 0.01 N, and balanced Ti. The Ti–4.5A1–3V–2Fe–2Mo (SP-700) alloy used in this study consists of 4.74 Al, 2.26V, 1.84 Fe, 1.89 Mo, and a balance of Ti. Both of these alloys were in the mill annealed condition as received. All specimens were welded in the as-received condition with the welding direction normal to the rolling direction. A 5 kW CO_2 laser was used for autogenous bead-on-plate welding in full penetration. The primary welding parameters included a laser power of 2800 W and a travel speed of 1000 mm/min; and the focal point was located 0.5 mm under the top surface of the plate. High-purity Ar was used as the backing and trailing gas to prevent oxygen and nitrogen contamination from the atmosphere. Helium (He) was purged to the fusion zone (FZ) to blow the plasma plume away. After X-ray examination, all of the welds were confirmed to be free of any detectable defects. The weldment in the as-welded condition was named the AW specimen. Some of the AW specimens were subjected to PWHT ranging in temperature from 482 to 704 °C (900–1300 °F) for 1 h in a vacuum, followed by Ar-assisted cooling to room temperature. For heat-treated welds, the last 3 digits represent the aging temperature; for example, W482 is the designation for the weld with the PWHT at 482 °C for 1 h.

A Vickers micro-hardness tester was used to measure the micro-hardness of different regions in a weld under a load of 300 g for 10 s. A double-edged notched specimen was applied for the notched tensile test, which used a sharp notch with a tip radius of approximately 100 μm and a notch depth of 7.0 mm [24]. For the testing, the notches were located at the center of the FZ to ensure crack growth along the weld centerline during tensile loading. Notched tensile tests were performed in air at room temperature with a constant displacement rate of 1.0 mm/min. The results were the average of at least three specimens for each testing condition. The specimens for metallographic observations were polished and etched in a solution composed of 10% nitric acid, 5% hydrofluoric and 85% water. The detailed microstructures of the fusion zone were examined using a transmission electron microscope (TEM) operated at 200 KV. The fracture features of various notched tensile specimens were inspected using a scanning electron microscope (SEM).

3. Results and discussion

3.1. Microhardness measurements

Fig. 1 shows the macroscopic cross section of the dissimilar laser weld and the distribution of microhardness from the FZ to the base metal (BM) for the weld under the AW or PWHT conditions. The FZ was relatively wide on the top weld side and showed a narrow throat in the middle (Fig. 1(a)). The low energy input of laser welding was responsible for such a narrow FZ and heat-affected zone (HAZ). A drastic transition in microstructure/microhardness from the FZ to the BM was expected to occur over the short distance in such a dissimilar weld. Under the AW condition (Fig. 1(b)), the FZ hardness was as high as HV 400. With a PWHT at 482 °C (i.e., the W482 specimen), the FZ hardness of the dissimilar weld approximated to HV 440, which implied an

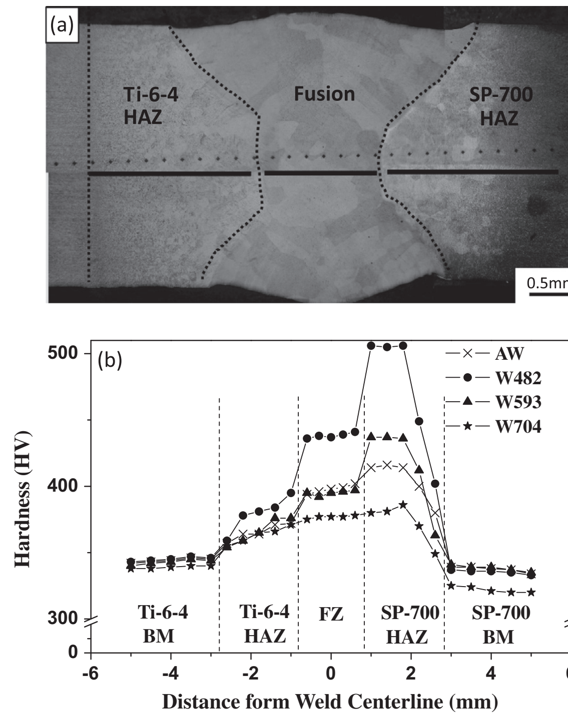

Fig. 1. Micro-hardness measurements in distinct regions of the dissimilar welds with PWHT in the temperature range of 426–704 °C.

age-hardening effect during PWHT. Moreover, the FZ hardness of the W593 specimen was slightly lower than that of the AW specimen. A decrease in FZ hardness to HV 385 was observed for the weld with a PWHT at 704 °C.

Concerning the changes in the HAZ hardness of the weld, the T-6-4 side exhibited characteristics distinct from those of SP-700. The results indicated the HAZ hardness of the T-6-4 side was less sensitive to PWHT conditions. A gradual increase in hardness from the BM to the fusion boundary was obtained in the Ti-6-4 side, regardless of the PWHT temperature. However, a sharp increase in and great variation of HAZ hardness was identified in the HAZ of the SP-700 side for the welds with distinct PWHTs. The coarse-grained HAZ in the as-welded SP-700 weld, which was heated above the β-trans temperature of approximately 900 °C, consisted of the fine $\alpha + \beta$ structure [22]. This was the result of higher hardness therein [22]. The HAZ hardness in the SP-700 side was over HV 500 in the W482 specimen, but dropped to HV 390 in the W704 specimen. By contrast, the mill-annealed BM was much softer than the FZ and HAZ of any of the welds.

Fig. 2 displays the changes in FZ hardness with the PWHT temperatures for the Ti-6-4 to SP-700 dissimilar welds, as compared with the Ti-6-4 [26] and SP-700 [23] homogeneous laser welds. The results indicated that the FZ hardness of the Ti-6-4 weld was insensitive to PWHT, whereas the SP-700 and dissimilar welds were sensitive to the PWHT temperature, particularly for the SP-700 welds. The variation in FZ hardness between those welds was the results of microstructural effects, which might be associated with their chemical compositions. Furthermore, the FZ hardness of the dissimilar weld fell between that of the Ti-6-4 and SP-700 homogeneous welds at the specific PWHT. With the PWHT at 704 °C, the coarsening of FZ microstructures limited the deviation in hardness range among the specimens.

3.2. Microstructural observations

SEM micrographs of the microstructures of various specimens are presented in Fig. 3. The microstructure of both titanium plates