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Microstructure characterization of laser welded Ti-6Al-4V fusion zones

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ABSTRACT

The as-welded microstructure of laser-welded Ti-6Al-4V is characterized as a function of CO2 key-hole mode laser welding speed. Martensitic α′ is the predominant phase, with some α and retained β. Phase transformation is affected by the cooling rate through laser welding speed. A higher welding speed of 1.6 to 2.0 m/min produced more martensite α′ and less retained β in the welds. 1.4 m/min welding speed produced small amounts of α, besides the martensite α′. A trace of δ titanium hydride phase seems to have formed in the weld fusion zone. Moiré fringes are a common feature in the TEM microstructure, due to abundance of multi-phase interfaces. Tensile twins and clusters of dislocations indicate that plastic deformation has happened in the as-welded microstructure, indicating the local stress levels to be approaching the yield stress on-cooling during laser welding.

1. Introduction

Ti-6Al-4V is a widely used hcp-α and bcc-β two phase titanium alloy that can have modifiable mechanical properties from various microstructures, depending on the thermal conditions on-cooling from the β-phase field at high temperatures. A low cooling rate leads to a diffusion-controlled formation of α-phase lamellae and retained β lamellae with highly coincident α/β interfaces. A high cooling rate leads to a diffusionless formation of α′ martensite lamellae and retained β lamellae. The strength of the alloy increases only slightly due to the martensite structure and mostly due to grain refinement [1].

Welding introduces non-equilibrium heating and cooling, thus complicating the microstructure evolution and its interpretation [2]. Following laser welding, the fusion zone microstructure has been identified as α and β "basket weave" Widmanstätten α and retained β [3–5], or martensitic α′ along with α and β [6,7]. In the melt-in mode of laser welding, such as powder deposition in freeform fabrication, the microstructure tends to be Widmanstätten α and β. In the key-hole mode of laser welding, the microstructure tends to be martensitic. Clearly, the types of microstructure and properties of weldments are sensitive functions of thermomechanical process parameters used in laser welding. However, within the key-hole mode laser welding regime, the effect of the cooling rate on phase transformation and microstructure of Ti-6Al-4V is still not well understood. This study aims to investigate the phase transformation behavior and resultant microstructure of the Ti-6Al-4V alloy as a function of welding speed (cooling rate) under key-hole mode laser welding.

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2. Experimental Procedure

2.1. Materials and Welding Procedure

The titanium Ti-6Al-4V, annealed, 6 mm thick sheet with a brushed surface of a 1.5–3.5 μm roughness, is used as the base metal. The alloy has the following chemical composition: 6.0 Al, 4.0 V, 0.20 O, 0.3 Fe, 0.015 H, 0.06 C, 0.05 N (wt.%) and titanium (Bal.). Weld specimens are fabricated by laser welding with a helium shielding. A 15 kW maximum output continuous CO_2 laser (TRUMPF TLF15000) is used to weld the straight-edge butt joint of the 200 mm × 100 mm sheets with no gaps in between. During the autogenous welding, a copper backing strip is used to support weld root formation. The base sheets are rigidly clamped to obtain low angle distortions of the joints. The laser beam is focused on the surface of the sheet with a spot radius of 1 mm. A front and back shielding, provided by gas trailers, is supplied with a high purity helium gas at a flow rate of 28 l/min to protect the molten pool and heated zone from oxidation. The parameters for laser welding are selected following an experimental optimization for the penetration, bead shape, weld porosity, and joint strength: 6 kW laser power, and 2.0 m/min, 1.6 m/min, and 1.4 m/min welding speeds (v).

2.2. Microstructure Analysis

The microstructure of the laser welds is characterized by X-ray diffraction (XRD), optical metallography, and transmission electron microscopy (TEM). The XRD measurements are carried out using an X'Pert PRO X-ray diffractometer with a Cu K_α radiation (λ = 0.15406 nm) and a BLK2 cooling cycle system. The scanning step size is 0.026°, and the scanning range is 15° to 120° (continuous). The scanning speed is 0.4377°/s with the current and voltage at 40 mA and 40 kV, respectively.

The optical microscopy specimens are mounted in epoxy, grinded, polished, and etched with the Kroll's reagent (13 ml HF, 26 ml HNO_3 and 100 ml H_2O). High-resolution microstructure of the as-welded fusion zone is characterized using a JEM 2010 TEM. The TEM samples are prepared using a standard procedure involving ion milling. The TEM parameters are as follows: 200 kV voltage, 96 μA dark current, 128 μA emission current, 109.8 pA/cm^2 current density, 1–8 s exposure time, and magnification between 20 k and 200 k times.

3. Results

3.1. Phase Constituents of Welds

The phases identified in the center of the as-welded fusion zones include hcp-α′ martensite, some amount of hcp-α solid solution, and a small amount of retrained bcc-β phase (Fig. 1). A comparison with the standard α′ PDF (Powder Diffraction File) card indicates that the lattice planes (10$\bar{1}$0), (0002), (10$\bar{1}$1), (10$\bar{1}$2), (11$\bar{2}$0), (10$\bar{1}$3), (20$\bar{2}$0), (11$\bar{2}$2), (20$\bar{2}$1), and (20$\bar{2}$2) are present with the samples.

α-Ti also possesses the hcp crystal structure and generally has a smaller lattice parameter than the martensitic α′. There is a small quantity of α phase in the centers of the fusion zones of the more slowly cooled welds. When the welding speed is slowest (v = 1.4 m/min), the α(20$\bar{2}$0) lattice plane is present. However, the α(20$\bar{2}$0) plane is not observed in the fusion zones of the faster cooled specimens (v = 1.6 m/min and v = 2.0 m/min). The effect of the cooling rate on β to α phase transformation will be explained later.

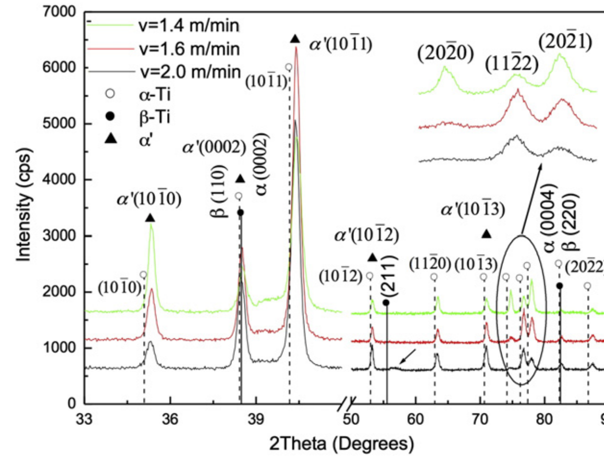

Fig. 1 – X-ray diffraction results of the weld fusion zones.

A comparison with the standard β-Ti PDF card reveals that a weak peak of β-Ti is present in the as-welded fusion zone when the welding speed is 2.0 m/min. Because the β(110) peak overlaps with α′(0002) peak, and β(220) peak overlaps with α(0004) peak, the weak peak from β(211) (indicated by the arrow in Fig. 1) is the only positive indicator of the presence of β in this set of XRD results. When welding speed decreases to 1.6 m/min and then 1.4 m/min, lattice plane β(211) is not observed.

To estimate the α′-Ti/β-Ti ratio in the titanium laser welds, a quantitative analysis is conducted using the reference intensity ratio (RIR) method, along with a quantitative phase analysis using the JADE software [8]. The results indicate that the weight fraction of α′ is 96%, and retained β is 4% in the 2.0 m/min specimen. The weight fraction of α′ is 93%, and the

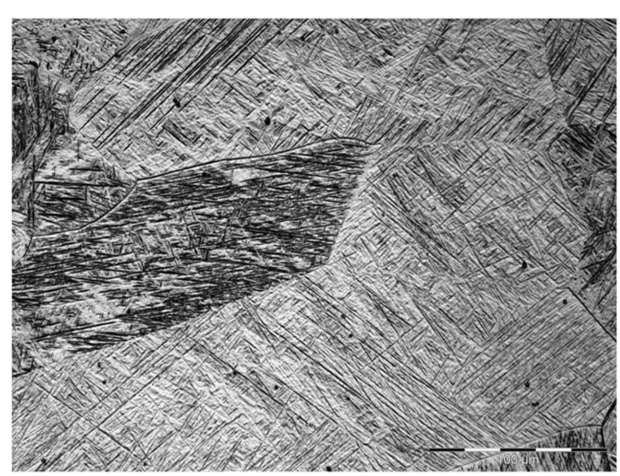

Fig. 2 – Typical optical microstructure near the center of the as-welded fusion zone.