Materials Science & Engineering A 677 (2016) 50–57

Contents lists available at ScienceDirect

Materials Science & Engineering A

journal homepage: www.elsevier.com/locate/msea

Microstructure, texture and mechanical properties of commercial high-purity thick titanium plates jointed by electron beam welding

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ARTICLE INFO

Article history:
Received 2 May 2016
Received in revised form
8 September 2016
Accepted 9 September 2016
Available online 9 September 2016

Keywords:
Electron beam welding
Titanium
Microstructure
Texture
Schmid factor

ABSTRACT

Electron beam welding (EBW) is a fusion joining process particularly suitable for the welding of thick titanium plates. In the present work, commercial high-purity titanium plates with a thickness of 30 mm were welded by EBW. Color metallography and electron backscattered diffraction (EBSD) were used to investigate the microstructure and texture after welding. The results show that the grains become elongated or coarsened in the weld zone (including the fusion zone and the heat-affected zone). Meanwhile, as revealed by the (0001) pole figures, the texture of the weld zone is enhanced. Despite the grain coarsening, the welded plates exhibit higher yield strength than the base metal. A Schmid factor analysis revealed that this increase in yield strength could be attributed to texture strengthening. Specifically, the grains in the weld zone are re-oriented. For the weld zone, the Schmid factor is relatively small for prismatic slip, which is the most easily activated deformation mode for titanium at room temperature. Compared to the base metal, the Schmid factors for $\{10\bar{1}2\}$ twinning and $\{11\bar{2}2\}$ twinning are larger for the weld zone. The EBSD observations confirmed that a large number of $\{10\bar{1}2\}$ twins and $\{11\bar{2}2\}$ twins are formed in the weld zone during tension. However, the plastic strain caused by the twin formation is much smaller than that caused by the prismatic slip in the base metal. As a result, necking occurred in the base metal during the transverse tensile tests.

1. Introduction

Titanium and its alloys are widely used in the marine, aerospace and biomedical industry due to their excellent properties, e.g., their high specific strength, good corrosion resistance, high toughness and excellent biocompatibility [1–4]. To fabricate complicated titanium components for automotive parts, satellite launch vehicles and aircraft turbine engines, new kinds of welding techniques have been introduced [5]. To date, several different welding methods, including friction stir welding, laser beam welding, gas tungsten arc welding and electron beam welding (EBW), have been employed to weld titanium [6–8]. Among these methods, EBW is especially suitable for the welding of thick titanium plates. Compared to arc welding processes, in the EBW process, the joint depth can be achieved with a higher beam power density and a lower heat input [9–11]. This generally results in a less coarse grain structure and superior mechanical properties. In order to optimize the welding parameters, it is desirable to understand the evolution of the microstructure during EBW and the relationships between the microstructure and the mechanical properties.

Previous studies have confirmed that the mechanical properties of titanium alloys joined by EBW were comparable to those of bulk titanium [12]. This was primarily attributed to the unique microstructure formed during the complex fast cooling and rapid solidification processes [9,13,14]. For thick weldments, the mechanical properties can vary significantly along the thickness direction due to the heterogeneity in microstructure, and were demonstrated to be affected by the selected welding parameters and the geometry of the actual joints [15,16]. It was reported that the mechanical properties of bell-shaped welds with a homogeneous microstructure were better than those of chock-shaped welds with a heterogeneous microstructure [15]. Therefore, methods for controlling the microstructure and the geometry design are important for achieving high-performance thick weldments. Despite the above mentioned efforts, the evolution of the microstructure and texture during the EBW of commercial titanium parts, especially when welding plates with a larger thickness, is still not fully understood.

This study aimed to investigate the effect of the EBW process on the texture and grain structure of thick titanium plates, and to

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http://dx.doi.org/10.1016/j.msea.2016.09.030
0921-5093/

assess the effect of a texture variation on the joint's performance. For this purpose, two hot-rolled high-purity commercial titanium plates with a thickness of 30 mm were butt-welded in vacuum, and then the microstructure of the welds was systematically studied by color metallography and employing electron backscatter diffraction (EBSD) techniques. Based on the orientation data gathered through EBSD, the activation of prismatic slip and twinning was analyzed in various regions of the welds via a Schmid factor analysis. The obtained results proved valuable for understanding the evolution of the microstructure during EBW and the relationships between the microstructure and the mechanical properties of thick pure titanium welds.

2. Material and methods

Commercial ultra-pure titanium (ASTM Grade 1) containing 0.011 wt% C, 0.035 wt% Fe, 0.001 wt% H, 0.002 wt% N and 0.038 wt% O as impurities was used as raw material in this study. The as-received titanium was hot-rolled into plates with a thickness of 30 mm. Two of these plates were then joined by EBW, with the welding direction (WD) being parallel to the transverse direction (TD) of the thick plates. The EBW was performed under vacuum conditions and the welding parameters are described in detail in Table 1. To assess the joint efficiency, uniaxial tensile tests were conducted on the welds at room temperature at a strain rate of 10^{-3} s^{-1}. Fig. 1a illustrates the orientations of the weld zone and the tensile samples with respect to the rolled titanium plate. In the figure, ND and TD denote the normal direction and the transverse direction of the rolled plate, respectively. As shown in Fig. 1a and b, the tensile samples were cut from different layers of the welded plates, i.e., the top, middle and bottom layers. The dimensions of the tensile samples are illustrated in Fig. 1c. To validate the reproducibility of the results, each kind of test was repeated at least three times.

Table 1
Welding parameters used for the EBW of thick titanium plates.

Machine setting	Parameter
Accelerating voltage (kV)	150
Focus current (mA)	2250
Welding speed (mm/s)	15
Beam current (mA)	90
Scanning pattern	Circle
Scanning amplitude (mm)	0.5
Scanning frequency (Hz)	8000

To reveal the evolution of the microstructure and texture during welding, the cross-section of the joint vertical to the WD (cp. Fig. 1a) was examined by optical microscopy (OM) and EBSD. For the latter, a field-emission scanning electron microscope (SEM, Tescan MIRA3) was used, which was operated at an acceleration voltage of 20 kV, with the step size varied between 2 and 6 μm. The data acquisition and data analysis were carried out using the HKL Channel 5 software. To ensure a good surface quality of the test samples for the OM and EBSD measurements, the samples were subjected to an electrolytic polishing in a solution of 10 mL perchloric acid and 90 mL methanol at −30 °C and 17 V for 150 s. In addition, for the OM observations, the samples were etched for 25–35 s with a modified Weck's reagent consisting of 2 g NH_4FHF, 25 mL ethanol and 100 mL distilled water. Then, crossed polarized light was used to reveal the grain structure.

3. Results and discussion

3.1. Macro- and micro-structure of the Ti plates after EBW

Fig. 2 shows the EBSD map and pole figures obtained for the base metal, revealing that the original thick titanium plate exhibits a twin-free equiaxed grain structure with an average grain size of ~51 μm. In the EBSD map, the grains were colored according to their crystallographic orientation relative to the TD. The {0001} pole figure indicates that the base metal has a bimodal texture with peaks tilted away from the ND to the TD, which is typical for hot-rolled titanium plates [17].

Fig. 3 shows a macrograph of a titanium plate after EBW. Clean and uniform weld beads were observed on the RD-TD cross-section. Here, RD denotes the rolling direction of the hot-rolled plate. No welding defects, such as porosity and distortions, were observed. A convex weld line was found on the top surface of the welded plates, as clearly revealed by the macrograph of the RD-ND cross-section. This suggests that the thick titanium plates could be successfully jointed by the EBW process with the welding parameters used. Crossed polarized light was employed to reveal the grain structure on the transverse cross-section of the titanium joint. Fig. 4a shows a low-magnification macrograph of the weld beads, which confirms that the microstructure is free of defects in the weld zone. Moreover, the weld zone features a keyhole shape penetrating through the thick titanium plate. According to the difference in microstructure, EBW joints can be generally divided into three distinct zones: base metal, fusion zone and heat-affected zone. In general, the heat-affected zone corresponds to a narrow transition region between the base metal and the fusion zone. However, in the present sample, no well-defined boundaries could be found between any two neighboring zones. Therefore, the boundaries of the different zones (superimposed in Fig. 4a) were estimated according to the locations of the weld root, the weld toe and the observed trend in grain size variation [18]. As shown in Fig. 4a, the widths of the fusion zone and the heat-affected zone vary from the top to the bottom of the thick plates. The width of the fusion zone is about 4 mm at the top and 1.5 mm at the bottom, whereas the width of the heat-affected zone changes from 1.5mm at the top to 0.8mm at the bottom, respectively. The enlarged micrographs (Fig. 4b–d) indicate that the microstructure obviously varies between the different zones. The fusion zone features a number of coarsened grains due to the severe welding heat generated during the EBW. In addition, the grains in the heat-affected zone are also coarsened and elongated toward the RD. This can be clearly seen in the regions close to the top surface of the weld head (Fig. 4e) and might be ascribed to the presence of a heat gradient in the transition region between the fusion zone and the base metal.

Fig. 5a–c show representative inverse pole figure maps obtained for the top, middle and bottom sections of the sample jointed by EBW. They reveal that the heat-affected zone mainly consists of coarsened and elongated grains. The grains were more severely coarsened in the fusion zone, and some grains exhibit a columnar microstructure (approx. 0.5–1.0 mm in length and 0.1–0.3 mm in width). The average grain size in different regions of the welded sample was estimated based on the EBSD data presented in Fig. 5 and is compared in Table 2. Furthermore, in the fusion zone, most of the grains are extended along the ND with an inclination angle of 10–35° in the top layer, whereas in the middle and bottom layers almost all grains are extended along the RD (cp. Fig. 5a). The formation of the columnar grains in the fusion zone might probably proceed as follows: It was reported that grains tend to grow in the direction of the heat gradient during welding solidification [19,20]. Since the cooling rate is very high, the grains tend to nucleate at the fusion boundary and grow quickly towards the weld centerline. Consequentially, coarse columnar grains are