Vacuum 146 (2017) 136–141

Contents lists available at ScienceDirect

Vacuum

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

Microstructure and properties of titanium alloy electron beam weldments based on the different heat input conditions of the same line energy

Fuyang Gao*, Qi Gao, Peng Jiang, Zhiying Liu, Zhiqian Liao

Luoyang Ship Material Research Institute, Luoyang, 471000, China

ARTICLE INFO

Article history:
Received 30 August 2017
Received in revised form
22 September 2017
Accepted 23 September 2017
Available online 27 September 2017

Keywords:
Ti6321
Electron beam weld
Microstructure
Properties

ABSTRACT

Electron beam welding (EBW) was applied to 20 mm thick marine high-strength titanium alloy Ti6321 with different heat input conditions of the same line energy, and microstructure, microhardness and tensile properties of the defect-free welded joints were examined. The results show that for small heat input (SHI) weld metal, martensite α' phase was wide and intertwined and the residual β was relatively high. For large heat input (LHI), martensite α' was relative small. Microstructure of the HAZ is inhomogeneous. For SHI, β phase collected in fusion line, and the heat affected zone of SHI had more residual β phase than that of LHI. XRD results indicate that the weld metal of LHI nearly consists of α' martensitic phase but small quantity of β phase. However, the weld metal of SHI exists α'martensitic phase, β phase and some α phase. Microhardness values in the centre of weld metal of SHI decreases greatly because of α phase. While hardness of LHI weld metal is consistent. The fracture locations of LHI EBW joint specimens are in base metal, and the UTS of the joints reach 935 MPa. The fracture locations of SHI EBW joint specimens are in weld metal, and the UTS of the joints reach about 905 MPa.

1. Introduction

Titanium and titanium alloys are excellent candidates for aerospace and marine applications owing to their high strength to weight ratio and excellent corrosion resistance [1]. But Titanium requires special attention in all the areas of processing, especially in welding. Titanium is very easily reactive to most atmospheric gases including hydrogen, nitrogen, and oxygen, at temperatures above 300 °C [2,3].

As a high energy beam machining technology in twenty-first Century, electron beam welding technology has the characteristic as: high energy density (10^7 W/cm^2), large weld depth width ratio which can be as high as 60:1, the advantages of small deformation and stability during weld process etc. [4–6]. And high vacuum inside the chamber also provides good protection for molten pool metal of titanium alloy from contamination, and ensures high welding quality [3,7–10]. Electron beam welding (EBW) is considered as the most suitable welding technique to joining the thick titanium plate in the aerospace industry due to the excellent weld quality, large depth penetration and the high vacuum environment [1,2,4,7].

Many researchers have investigated the microstructure and mechanical properties of titanium electron beam weldments [3,11–14]. However, there is hardly any literature reporting about the effect of beam processing parameter with different patterns on the microstructure and mechanical properties of titanium alloy joints [12,13], especially no one on microstructure and properties of marine high-strength titanium alloy electron beam weldments based on the different heat input conditions of the same line energy. Most of the existing researches focus on the influence of welding parameters, such as welding current, welding voltage and welding speed, mainly to study the impact of single welding parameters on the quality of the weld. However, welding is the result of the interaction of various parameters. The function of each parameter is to generate heat, and then to ensure the melting of the base metal to form the weld seam. So there is a process window that can realize welding. In the process window, the welding line energy, which refers to the welding heat in the unit length welding, will be at a stable level, that is, the temperature above the melting point, the melting of the base metal can be realized. But what kind of effect on the microstructure and properties of welding in

* Corresponding author.
E-mail address: gaofuyang@126.com (F. Gao).

https://doi.org/10.1016/j.vacuum.2017.09.038
0042-207X/

different welding heat input have not yet been seen in the research reports. So researching the difference of the microstructure and property under the different heat input conditions of the same line energy, and revealing the effect are the focus of this study.

2. Materials and experimental procedure

The base metal is Ti6321 titanium alloy in annealing state. The chemical compositions of base metal are shown in Table 1 and its microstructure is presented in Fig. 1. Fig. 1a is the image of optical microscope (OM), while Fig. 1b is the amplifying image of OM. From Fig. 1, it can be seen that the base metal consists of typical bimodal microstructure with primary equiaxed α phase and partially transformed β phase containing aciculate α.

Before welding, the surface of titanium alloy plates are polished with emery paper and ablated in aqueous solution of 3%HF +35% HNO3. Thick plates in annealing condition with dimensions of 200 mm × 100 mm × 20 mm were utilized in the present investigation. The electron beam butt joints are carried out by full penetration welding. The welding parameters are listed in Table 2. The line energy can be described as Eq. (1).

$$Q = \eta UI/V. \tag{1}$$

Q is line energy; η is thermal efficiency, which is relate with welding distance and the focusing current, and the thermal efficiency η for both the electron beam penetration welding is taken as 0.95; U is welding voltage; I is welding current; V is welding speed. For SHI, $Q_{SHI} = \eta UI/V = 0.98 \times 150$ KV × 40mA/200 mm/min = 1710 J/mm; and for LHI, $Q_{LHI} = \eta UI/V = 0.98 \times 150$ KV × 200mA/1000 mm/min = 1710 J/mm. The two specifications of welding are different, but they have the same line energy with different heat input.

After welding, the microstructure and properties of both joints with different welding parameters are investigated. The specimens of both joints for observing the metallography were cut perpendicular to the weld bead, and cross-sections were prepared for metallographic analysis by grinding and polishing techniques. The microstructure of the welded joints was observed by OLYMPUS GX71 Observer. D8 ADVANCE X-ray diffract meter (XRD) was used to test the phase constituent of weld metal. Besides, TEM observation was conducted by JEM-2100 TEM. 3 mm diameter disk samples with a hole in the centre were used for TEM observation and the samples were prepared under the temperature −20 °C by electropolishing in electrolyte of 6%HClO4 + 34%C4H9OH + 60% CH3OH. VMH-I04 microhardness Vicker was used to test the microhardness of weld metal, fusion zone, HAZ and base metal with load 200 N and holding time 10 s. The tensile strength test was carried out by INSTRON5982.

3. Results and discussion

Macrostructures of the thick EBW Ti6321 joints with different welding parameters are shown in Fig. 2. The joint was obtained using the above welding parameters with the same line energy, and there are no volumetric defect. The SHI got taper shaped weld, as shown in Fig. 2a, while LHI was parallel shaped weld, as shown in Fig. 2b. Similar with the conventional fusion welding method, according to the grain size and microstructure, the joints can be divided into four zones: weld metal (WM), fusion zone (FZ), heat affected zone (HAZ) and base metal (BM). Weld metal and heat affected zone is clearly distinguished from base metal, and fusion zone is the solid-liquid two phase zone with fusion line between heat affected zone and weld meta.

The coarse columnar grain can be seen in Fig. 3 a. Martensite α phase was grown in parallel to each other mainly, and there were also some staggered grown, as shown in Fig. 3c, which was about 1 μm width, and the residual β phase distributed in the interface of martensite phase at higher levels, as shown in Fig. 3f. Due to the long time stayed in high temperature, martensite α phase grown big, meanwhile for the slow cooling speed and small temperature gradient, martensite α phase became wide and intertwined. The cooling rate was slow, so the residual β were relatively high.

The fine columnar grain can be seen from Fig. 3 b. Martensite α was intertwined, as shown in Fig. 3d. The α phase was width of about 0.5 μm, aspect ratio greater than 10: 1, as can be shown in Fig. 3e. There was a small amount of flaky α phase with different orientations around the martensite, and the residual β phase was distributed in the interface between martensite and flaky α-phase. For short time dwelled in high temperature, martensite α phase had no time to grow. Because of the high cooling speed and great temperature gradient, martensite α grown along the direction of maximum temperature gradient, so martensite α was relative small in width and parallel to each other. The fast cooling speed made it hard to precipitate β-phase, so supersaturated martensite formed.

Fusion line of SHI was not obvious, but some dark β phase can be seen in the location of fusion line, as shown in Fig. 4a. That is probably due to slow cooling, part β stabilizing element precipitated during solidification, resulting in β phase collected in fusion line. Fusion zone of LHI was obvious. Weld grains were coarse, while heat-affected zone grains were relatively small, as shown in Fig. 4b. Because of the rapid cooling, β stabilizing element had no time to precipitate, thereby supersaturated martensite forming. So there was no significant accumulation of β-phase. The HAZ near weld metal consists of acicular martensite and a small portion of α phase.

The microstructure of heat affected zone in both weld procedures consists of primary α phase and transformed β containing aciculate α, almost equal to base metal, as shown in Fig. 5a and b. But the content of β phase had great difference. The heat affected zone of SHI had more residual β phase than that of LHI. From Fig. 5a, it can be seen that the border of acicular α phase and β phase was ambiguous, and equiaxed α grown large. However, in Fig. 5b the border of acicular α phase and β phase was clear. This is because the temperature of heat affected zone of SHI was higher than that of LHI, which made the equiaxed α and β phase growing.

In contrast, it can be found that there are still a lot of differences except the microstructures. The weld phase composition was analyzed by XRD, as can be seen in Fig. 6. From the phase constitution above, there definitely have some difference between the both joints. It indicates that the weld metal (WM) of LHI nearly is composed of α' martensite but small amount of β phase. However, the weld metal (WM) of SHI exists α' martensitic phase, β phase and some residual α phase. The initial α and β phase transforms into high temperature β phase due to the influence of the welding heat input. The rapid cooling rate of the electron beam welding is such fast that martensite occurs during cooling. When the temperature is reduced to the solid-liquid two-phase coexistence zone, the primary α phase is nucleated in the surface of the fusion zone near weld, and grows toward the centre of the weld metal along the maximum direction of the temperature gradient, as shown in Fig. 4. The columnar crystals go through β grains and divide them, presenting parallel lath-shaped and epitaxial solidification.

Table 1
Chemical composition of Ti6321 titanium alloy (mass fraction, %).

Al	Nb	Zr	Mo	Fe	Si	C	N	Ti
5.5–6.5	2.5–3.5	1.5–2.5	0.6–1.5	0.25	0.15	0.1–0.2	0.05	Bal