Vacuum 155 (2018) 496–503

Contents lists available at ScienceDirect

Vacuum

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

Effect of heat treatment and laser shock peening on the microstructures and properties of electron beam welded Ti-6.5Al-1Mo-1V-2Zr joints

Weiju Jia[a,*], Hengzhang Zhao[a], Yaoxu Zan[a,b], Ping Guo[a], Xiaonan Mao[a]

[a] Northwestern Institute for Nonferrous Metal Research, Xi'an, 710016, China
[b] Taiyuan University of Technology, Taiyuan, 030024, China

ARTICLE INFO

Keywords:
Titanium alloy
Laser shock peening
Electron beam welding
Heat treatment

ABSTRACT

The effect of the heat treatment and LSP on the microstructures and properties of EBWed Ti-6.5Al-1Mo-1V-2Zr joint were investigated. The characteristic of microstructures, micro-hardness, tensile properties and fracture morphology of specimens were analyzed. The results show that the microstructure of original EBWed specimen contains columnar grains in the edge and equiaxed grains in the center of the FZ, and a large amount of acicula martensitic α′ precipitated within the grains. The microstructure in the HAZ contains a mixture of equiaxed β grains with acicula martensitic α′ and fiber α phase in it. The grain boundary α phases and secondary α phase precipitates in the FZ and HAZ, and the fiber α phase coarsen in the HAZ after heat treatment. The hardness of the whole welded joint have a little increasing after heat treatment, and the level of the hardness increases largely after LSP treatment. The LSPed specimens exhibit higher strength than that of the heat treatment specimens, and the strength of the LSPed specimen increases slightly with increase of LSP impacts. The dominant crack location and propagation path of EBWed Ti-6.5Al-1Mo-1V-2Zr joint are changed after LSP treatment.

1. Introduction

Titanium alloys are widely used in the aerospace applications because of their excellent strength-to-weight ratio and excellent intermediate temperature performance [1,2]. Under the demand of the development of the larger and complex airplane, several welding methods such as tungsten inert gas (TIG), laser beam welding (LBW), electron beam welding (EBW) and friction welding have been developed to fabricate high quality joint structures [3–5]. Especially, electron beam welding (EBW) is highly suited for joining titanium alloys, as the high vacuum inside the chamber where the process is carried out, shields hot metal from contamination. Moreover, compared with other welding processes, joint depth can be achieved with high beam power density and low heat input [6–9]. However, residual stresses always generated during welding due to the high thermal gradients and the associated microstructural changes during the process. These residual stresses have a detrimental effect on the mechanical behavior of structural parts [10]. Therefore, post-weld treatment should be carried out after welding. In practice, several approaches are adopted to eliminate the residual stresses in the welds, such as the heat treatment, the explosion and ultrasonic peening etc. [11,12]. Post heat treatment is a traditional method used after welding, it can efficiently improve the mechanical and chemical properties of the welded joint by relieving the residual stresses and modifying the microstructure in the heat treatable alloys [13–15]. However, its high costs and inconvenient process restrain its application especially for the large and irregular structures.

As a new surface modification technique, laser shock peening (LSP) treatment is capable of introducing deeper compressive residual stress and cold work in the near-surface layers without compromising the surface roughness [16,17]. Recent years, LSP has been introduced as a mean for improving the properties in welding [18,19]. Hatamleh et al. [20] found that the strength of 2195 Al-Li alloy joint can be increased by LSP. Xu et al. [21] investigated the microstructures and properties of EBWed joints of Ti-6.5Al-1Mo-1V-2Zr alloy after treated by LSP. They found that the micro-hardness of Ti-6.5Al-1Mo-1V-2Zr joint increased after LSP, and the elongation of EBW joints also increased obviously at 25 °C and 300 °C. Despite the numerous papers that deal with the microstructure and the mechanical behavior in welds of titanium alloys, information concerning the effect of post-weld treatment on the microstructure and mechanical properties of EBWed joint of Ti-6.5Al-1Mo-1V-2Zr alloy needs to be more detailed. Therefore, in the present study, the effect of the heat treatment and LSP on the microstructures and properties of EBWed Ti-6.5Al-1Mo-1V-2Zr alloy joints were investigated. The results will provide some important insights on the selection of post-weld treatment of EBWed titanium alloys.

* Corresponding author.
E-mail address: diana_1025@126.com (W. Jia).

https://doi.org/10.1016/j.vacuum.2018.06.057
Received 27 February 2018; Received in revised form 20 June 2018; Accepted 21 June 2018
0042-207X/

Table 1
Chemical composition of Ti-6.5Al-1Mo-1V-2Zr alloy (wt %).

Al	Mo	V	Zr	Si	Fe	C	Ti
6.47	1.56	1.43	1.86	< 0.04	≤ 0.02	≤ 0.010	Balance

Table 2
The main welding parameters used in this work.

Accelerating voltage	Focus current	Beam current	Welding speed
150 kV	2359 mA	180 mA	300 mm/min

Table 3
Parameters of laser shock peening.

Parameters	Value
Laser wavelength (nm)	1064
Pulse energy (J)	4 J
Pulse duration (ns)	20
Spot diameter (mm)	2.6
Repetition-rate (Hz)	0.5
lapping rate	50%

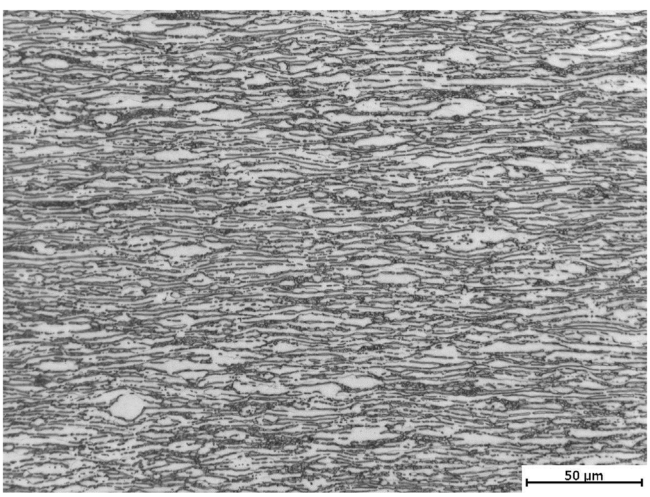

Fig. 1. Microstructure of original Ti-6.5Al-1Mo-1V-2Zr alloy.

2. Material and experimental procedure

The material used in the present study is Ti-6.5Al-1Mo-1V-2Zr alloy as hot rolled and annealed sheet of 5 mm thickness with the chemical composition presented in Table 1. The β transus temperature of the alloy was 990 °C. The sheet was chemically cleaned before double-sided EBW. The main welding parameters used in this work are listed in Table 2.

The LSP experiments were performed using a YAG laser operating at a repetition frequency of 0.5 Hz with a wave length of 1064 nm and pulse duration of 20 ns? The spot diameter was 2.6 mm and the pulse energy of laser was 4 J. For all specimens, the overlapping rate used in LSP was kept 50% between two adjacent spots. The water with a thickness of 2 mm was used as the transparent confining layer and the black tape with a thickness of 0.1 mm was used as the absorbing layer to protect the specimen surface from thermal ablation. The black tape was replaced after each impact during multiple LSP impacts. The LSP parameters were listed in Table 3.

The tensile specimens with a gauge length of 25 mm and width of 5 mm were electro-discharged machined from the base metal along the transverse and EBWed sheet perpendicular to the welding direction with the joint positioned in the middle of the gauge length. The tensile specimens were divided into four groups with different conditions: the first group was the welded specimens, the second group was the specimens vacuum annealed at 800 °C for 1 h, the third group was double-sided laser shock peened specimens, and the last group was the specimens vacuum annealed at 800 °C for 1 h following laser shock peening. All the testing results were average of three specimens.

Metallographic specimens crossing the different welding zones were cut from the EBWed sheet perpendicular to the welding direction, then ground, polished, and etched using Keller's reagent. Microstructures and fracture surfaces of the specimens were analyzed by an optical microscope (OM) Leica DFC320 and scanning electron microscope (SEM) SUPRA55, respectively. Micro-hardness was measured across the welded joint at a distance of 1 mm from the top surface, using a Vickers indenter with a load of 200 g and a dwell time of 10 s at an interval of 0.2 mm.

3. Results and discussion

3.1. Microstructures

Fig. 1 is an optical micrograph of the as received Ti-6.5Al-1Mo-1V-2Zr alloy. The initial microstructure consisted of α and β phase. All the α phase were elongated along the rolling direction, which is the typical microstructure of the rolled plate. The macroscopic view of one typical EBWed joint, without any post-weld treatment, is show in Fig. 2a. The specimen showed no evidence of porosity or other kinds of defects in welded joint. It can be seen clearly that the microstructure vary across the welded joint. The joint can be divided into 3 zones: the fusion zone (FZ), heat affected zone (HAZ) and base metal (BM). Fig. 2b–d shows the close-up views of the FZ in the joint. It is observed from Fig. 2b that the microstructure contains columnar grains in the edge and equiaxed grains in the center of the FZ. This is the typical characteristics of solidified microstructure. During solidification, grains grew towards the weld center owing to the effect of steep thermal gradient present at the weld interface than the weld pool center and this favors the columnar grains growth opposite to the heat extraction. In the same way, due to the rapid cooling and lower steep thermal gradient at the pool center, equiaxed grains were formed at the center of the welded zone [22]. In addition, a large amount of acicula martensitic α′ precipitated within the grains, as shown in Fig. 2c and d. For Ti-6.5Al-1Mo-1V-2Zr alloy, there are no enough β-stabilizing alloying elements can reserve the β phase to room temperature. Moreover, there is no time for the transformation of β phase to α phase under the rapid cooling rate during EBW. Therefore, many researchers observed the martensitic α′ phase in the FZ of EBWed titanium alloy joint [23–25]. The microstructure in the HAZ contains a mixture of equiaxed β grains with acicula martensitic α′ and some fiber α phase in it, as shown in Fig. 2e. Unlike FZ, the HAZ experiences distinct temperature gradient in terms of both maximum temperature and cooling rate during welding. The rolled fiber microstructure undergoes recovery and recrystallization under the thermal effect which results in the equiaxed β grains. Meanwhile, some amount of fiber α phase are retained due to the temperature did not exceed the β transus temperature completely.

The microstructures of post-weld heat treaded specimens are shown in Fig. 3. Compared with the original welded specimens (Fig. 2), there are several changes can be observed in the joint after heat treatment: 1) more homogeneous microstructures can be observed across the welded joint, as shown in Fig.3a; 2) the grain boundary α phases (GB α) precipitates in the FZ and HAZ, as shown in Fig. 3c and e; 3) the secondary α phase precipitates in the FZ and HAZ (Fig.3c); 4) the fiber α phases coarsen in the HAZ, as shown in Fig. 3e. These changes are the results of