Materials Characterization 145 (2018) 87–95

Contents lists available at ScienceDirect

Materials Characterization

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

Microstructural evolution and hardness response in the laser beam welded joints of pure titanium during recrystallization and grain growth

H. Liu[a,*], J. Shui[a], T. Cai[a], Q. Chen[a], X.G. Song[b], G.J. Yang[a]

[a] State Key Laboratory for Mechanical Behavior of Materials, Xi'an Jiaotong University, Xi'an 710049, China
[b] State Key Laboratory of Advanced Welding and Joining, Harbin Institute of Technology, Harbin 150001, China

ARTICLE INFO

Keywords:
Pure titanium
Laser beam welded joint
Heat treatment
Recrystallization and grain growth
Microstructural evolution
Hardness response

ABSTRACT

Microstructural evolution and hardness response in the laser beam welded joints of pure titanium during recrystallization and grain growth were investigated by means of electron backscatter diffraction and hardness measurement. The low-angle boundaries (LABs) and high local misorientations, in the as-welded heat affected zone (HAZ) and fusion zone (FZ), indicate the existence of plastic strains caused by the plastic strains due to the thermal stress and the non-equilibrium phase transformations. The recrystallization occurs in the HAZs during heat treatment, but the grain growth after recrystallization does not appear under the heat treatment conditions. Moreover as a result of the slightly high impurity contents in the as-welded FZ, no distinct recrystallization is found in the FZs in this work. During recrystallization in the HAZs, the coarse and unstrained grains with equiaxed shape and smooth boundary gradually consume the fine and strained ones with irregular shape and serrate boundary. Meanwhile, the LABs disappear and the low local misorientations replace the high ones in the modified grains. The recrystallization during heat treatment causes the decrease of plastic strains in the HAZs, which reflects on the descent of average hardness values based on the strain strengthening.

1. Introduction

Commercially pure titanium exhibits the good corrosion resistance and excellent biocompatibility, and thus has been widely used in the chemical and medical industries [1]. The fabrication of various titanium products in these fields highly depends on the welding and joining techniques, especially the laser beam welding owing to its small welding deformation and narrow weld shape [2–14]. In the past few years, a great number of studies have been conducted to the laser beam welding of pure titanium, and have mainly focused on the design optimization based on the relationships among the welding parameters, microstructures and mechanical properties [9–14]. Recently, the profound illuminations of microstructural characteristics and strengthening mechanisms in the joints of pure titanium have been gained, considering the non-equilibrium phase transformations during laser beam welding [13,14]. In particular, the non-equilibrium microstructures with abundant substructures have been found in the laser beam welded joints of pure titanium. The substructure boundaries or low-angle boundaries (LABs) are commonly believed to be the arrays of geometrically necessary dislocations, and thereby mean the existence of weak deformations or strains in the laser beam welded joints. However, the non-equilibrium microstructures in the joints are thermodynamically unstable, and the heat treatment after welding probably conduces to the formation of equilibrium microstructures by virtue of the recrystallization and grain growth. On the other hand, a large quantity of researches have been concentrated on the fundamentally physical understandings of recrystallization and grain growth during heat treatment in the severely deformed titanium, and the severe deformations are introduced by the cold rolling, the warm rolling and the equal channel angular pressing [15–19]. Unfortunately, little work has been made to deeply clarify the behavior of recrystallization and grain growth during heat treatment in the weakly deformed titanium generated by the laser beam welding. Therefore, the microstructural evolution in the laser beam welded joints of pure titanium during heat treatment is unclear as well as the hardness response. In this paper, the laser beam welded joints of pure titanium were handled under the various heat treatment conditions, the behavior of recrystallization and grain growth during heat treatment in the joints was discussed, and the microstructural evolution and hardness response during recrystallization and grain growth were investigated in detail.

2. Experimental

The as-received material was the pure titanium sheet with the

* Corresponding author.
E-mail address: hongliu@mail.xjtu.edu.cn (H. Liu).

https://doi.org/10.1016/j.matchar.2018.08.036
Received 29 October 2017; Received in revised form 24 July 2018; Accepted 20 August 2018
Available online 21 August 2018

thickness of 2.5 mm and the chemical composition of Ti-0.02C-0.004H-0.14O-0.01N-0.08Fe (wt%). The workpieces were bead-on-plate welded at 4 kW laser power under different traveling speeds by an IPG YLR-4000 fiber laser welding system. During welding, an argon shielding was utilized to minimize the surface oxidation. The as-welded joints were cut into the small specimens, which were sealed in the vacuum quartz tubes later. Finally, the heat treatment was carried out by a SX2-5-12TP electrical resistance furnace. The holding time ranging from 30 to 120 min and treatment temperature from 625 to 700 °C were implemented in this investigation. The samples before and after heat treatment were mechanically ground and then electro-polished. The polished specimens were examined by a Nikon MA200 optical microscope. Electron backscattering diffraction (EBSD) was realized by a Hitachi SU-70 scanning electron microscope incorporated with an EDAX Hikari camera. The step size of 2 μm was employed and the average confidence index (CI) from 0.4 to 0.56 was obtained in the raw EBSD data. The raw data were cleaned up using the grain CI standardization option followed by the grain dilation option to ensure reliability. The misorientation angles (MAs) less than 2° were deleted to eliminate the false boundaries caused by the orientation noise. The MAs between 2 and 15° (low MAs) defined the LABs, and the MAs above 15° (high MAs) pointed to the high-angle boundaries (HABs). A 5° exclusion angle together with the 5th nearest-neighbors was selected during the analysis of kernel average misorientations. The kernel average misorientation angles (KAMAs) below 1° (low KAMAs) denoted the low local misorientations versus the high ones, compared with the KAMAs above 1° (high KAMAs). The hardness measurement in the joints before and after heat treatment was performed by a HXD-1000TMC/LCD hardness testing device under a load of 0.98 N for a dwell time of 15 s with an interval of 0.1 mm.

3. Results and Discussion

3.1. Microstructural Characteristics in the As-welded Joint

Fig. 1 presents the macrostructure and orientation information in the as-welded joint of pure titanium at 4 kW–3 m/min. The sample reference directions are shown in the bottom left corner of Fig. 1a. The ND, RD and WD are respectively the normal, rolling and welding directions. The joint is composed of the base metal (BM), the heat affected zone (HAZ) and the fusion zone (FZ). The boundaries between the BM and HAZ are easily distinguished due to the different grain morphology, which are described by the dotted white lines. However, it is quite difficult to identify the fusion lines owing to the similar microstructures formed in the HAZ and FZ. In order to investigate the orientation information, the middle left part of cross-section in the joint is selected from the BM to weld centerline. The grain orientation map of selected cross-section is given in Fig. 1b, where the color coded triangle is displayed in the bottom left corner. The grains with irregular shape and serrate boundary are found in the HAZ and FZ, different from those with equiaxed shape and smooth boundary in the BM. Besides, the product α grain sizes at room temperature distinctly increase from the HAZ to FZ, dissimilar to the uniform grain size in the BM. It is tightly related to the increase of parent β grain sizes at elevated temperatures in the HAZ and FZ with the position moving to the laser heat source. As shown in Fig. 1c, a lot of HABs (the solid blue lines) appear in the joint, but a large number of LABs (the solid red lines) only emerge in the HAZ and FZ. As the arrangements of dislocations, the LABs can be roughly associated with the plastic strains. Fig. 1d gives the kernel average misorientation map of selected zone so as to estimate the plastic strains in the HAZ and FZ, and the color coded rectangles are shown in the bottom left corner. The kernel average misorientations reveal the local variations of lattice orientations in a given area defined by the investigators, and it is a good indicator of plastic strains in crystals [20–26]. The blue region is dominant in the BM, while the green and yellow regions are predominated in the HAZ and FZ. Opposite to the low ones in the BM, the high local misorientations are detected in the HAZ and FZ. The high local misorientations mean the existence of plastic strains in the HAZ and FZ. The strain-free grains with equiaxed shape and smooth boundary in the BM are the recrystallized structure after rolling and annealing. The welding temperature field changes the spatial and temporal variations of plastic deformations at elevated temperatures due to the thermal stress, and the plastic deformations at elevated temperatures interact with the non-equilibrium phase transformations during fast heating and cooling. Therefore, the strained grains with irregular shape and serrate boundary in the HAZ are attributed to the corporate effects of the non-equilibrium $\alpha \rightarrow \beta$ phase transformation during fast heating and the plastic deformations at elevated temperatures due to the thermal stress followed by the non-equilibrium $\beta \rightarrow \alpha$ phase transformation during fast cooling. However considering the melting process, the strained grains with irregular shape and serrate boundary in the FZ are connected with the combined effects of the plastic deformations at elevated temperatures and the non-equilibrium $\beta \rightarrow \alpha$ phase transformation during fast cooling.

The misorientation distributions in the as-welded joint of pure titanium at 4 kW–3 m/min are described in Fig. 2a, and the (0001) pole figures are inserted in the center part. The number fraction (NF) of high MAs is up to 0.89 in the BM, and the texture exhibits the bimodal distributions of (0001) basal plane. After welding, the NFs of low MAs markedly increase, and they are about 0.6 in the HAZ and FZ. The

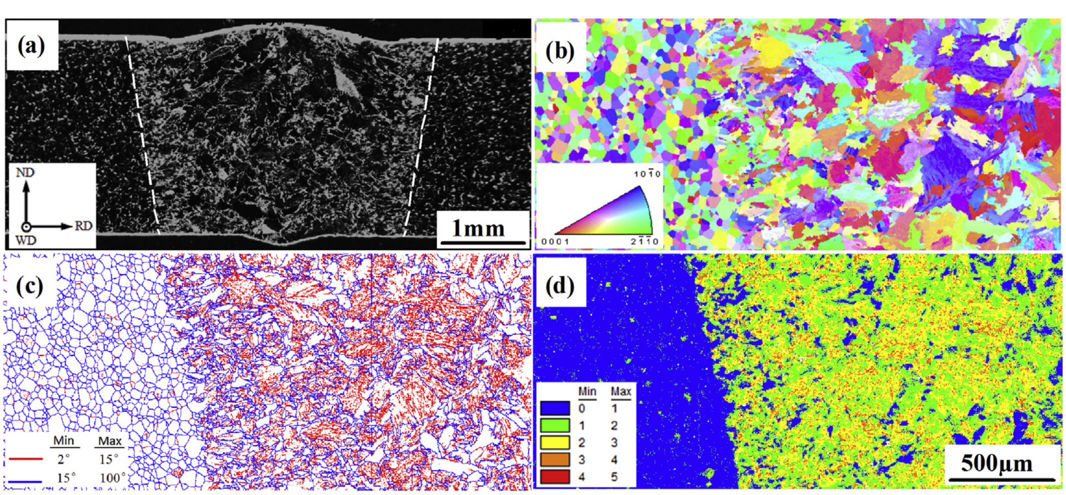

Fig. 1. Macrostructure and orientation information in the as-welded joint of pure titanium at 4 kW–3 m/min: (a) macrostructure; (b) grain orientation map; (c) grain boundary map; (d) kernel average misorientation map.