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Influence of welding speed on microstructures and mechanical properties of vacuum electron beam welded TZM alloy joints

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ABSTRACT

Butt joints of molybdenum-titanium-zirconium (TZM) alloy were welded by electron beam welding (EBW) and the influence of welding speed on the microstructures and mechanical properties of TZM joints were investigated in this paper. The color etching method was performed to obtain the orientation and phase distribution on weld zones (WZs) of the joints welded at different welding speeds. The electron backscatter diffraction (EBSD) and transmission electron microscopy (TEM) were conducted to further check the results of the color etching method. The results illustrated that the tensile strengths would reduce with the increasing welding speed within a certain range. When welding speed was 350 mm/min, the tensile strength was 403 MPa, while the tensile strength of the joint welded at the welding speed of 390 mm/min was 256 MPa. The segregation of the MoO_2 particles on grain boundaries (GBs) was also promoted with the increase of the welding speed, leading to the decrease of tensile strength and formation of severe intergranular fracture in the WZ.

1. Introduction

TZM (Mo-0.5Ti-0.08Zr-0.02C) alloy is one of the most promising molybdenum alloys, which is produced by the addition of zirconium and titanium as well as carbon into pure molybdenum [1–3]. Due to its good elastic modulus and a relatively higher recrystallization temperature as well as excellent mechanical properties at high temperature, TZM alloy has been widely used in aerospace, nuclear power and other industrial fields [4–7]. For extensive applications of TZM alloy in industrial fields, the welding of this alloy has attracted the broad attention of researchers.

In order to achieve the effective joining of TZM alloy plates, kinds of welding methods have been tried, such as friction stir welding and brazing [8,9]. The fusion welding methods, with the simple welding process, were particularly suitable for the joining of TZM alloy. Tungsten inert gas (TIG) welding of Mo-based alloys was investigated by plentiful scholars. Miller et al. [10] illustrated that the segregation of oxygen on grain boundaries (GBs) was produced in the weld zone (WZ). The addition of zirconium and boron as well as carbon into the weldment would displace the oxygen from GBs, leading to the enhancement of tensile strength and elongation. Tabernig et al. [11] carried out the TIG welding experiments on TZM alloy plates in an argon atmosphere. However, the results indicated that the protection of argon would not eliminate the segregation of oxygen on GBs in the WZ, resulting in the formation of intergranular fracture in the WZ. In addition, Wadsworth et al. [12] implied that the severe grain coarsening was produced at the WZ of the TIG welded TZM alloy joint and the width of the heat affected zone (HAZ) would be up to 20 mm.

The joining strength of Mo-based alloy is sensitive to the oxygen content and the energy density of the heat source as summarized above. Hence, EBW was the most suitable fusion welding method for the joining of Mo-based alloy on account of the protection of vacuum atmosphere and high energy density [13–15]. The results of the study investigated by Tabernig et al. [11] indicated that the

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tensile strength of EB-welded TZM alloy joint was obviously superior to that of the joint welded by the TIG welding method. In addition, Wadsworth et al. [12] also found that the grain sizes in the WZ of the EB-welded TZM alloy joint were significantly smaller than those of the TIG welded joint, leading to the enhancement of tensile strength of the EB-welded joint. Kohyama et al. [14] and Hiraoka et al. [16] believed that carbon element in an appropriate range would eliminate the segregation of oxygen on GBs, restraining the generation of intergranular fracture in the WZ. In general, the welding parameters, especially welding speed which can significantly influence the welding efficiency, would affect the distributions of precipitates, causing the embrittlement of welded joints. However, seldom relevant research reports was indexed. Thus, it is necessary to study the influence of welding speed on the mechanical properties of TZM joints. This study is aimed at the affecting mechanism of the welding speed on the microstructures and mechanical properties of EB-welded TZM alloy joints. Microstructural investigations into distinct WZs in different joints were discussed in detail. The tensile strength examination at room temperature was performed and the fracture morphology was analyzed by scanning electron microscope (SEM). The grain orientations and phase compositions were identified by orientation imaging microscopy and transmission electron microscopy (TEM), respectively.

2. Materials and experimental procedures

TZM alloy plates (Mo-0.5Ti-0.08Zr-0.02C) were chosen as the base material for EBW, which were produced by powder metallurgy and hot rolling process. The microstructure of base metal observed by optical microscopy (OM) was demonstrated in Fig. 1. Fig. 1 depicted that micropores were generated due to the characteristic of the powder metallurgy process and rolled grains were also produced after the hot rolling process. These TZM plates with a dimension of 100 × 25 × 3.0 mm were cleaned by sanding and acetone to remove stains before welding. Then TZM plates were clamped and welded in the EBW equipment under a vacuum degree of 4 × 10^{-2} Pa. In this paper, butt joints of TZM alloy were welded at an accelerating voltage of 70 kV and a beam current of 35 mA. The welding speeds were chosen as three sets of 350 mm/min, 370 mm/min and 390 mm/min for the comparative experiments.

Specimens for metallographic observation and tensile tests were incised by wire-cut electric discharge machine from welded

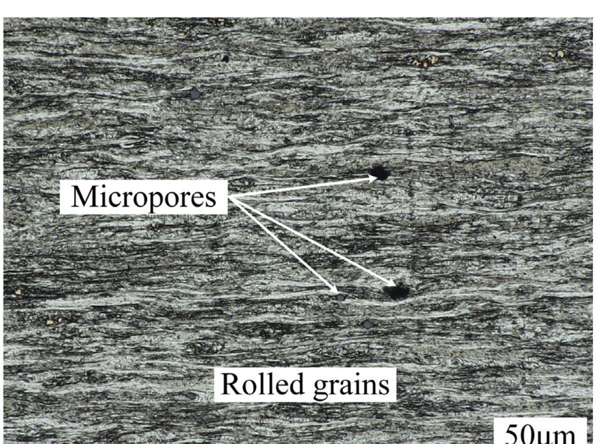

Fig. 1. Elongated grain structure of TZM alloy.

Table 1
Composition of the Hasson's etchant.

Reagent	C_2H_5OH	HCl (32%)	$FeCl_3$-$6H_2O$[a]
Volume	75 mL	25 mL	50 mL

[a] Solution of 1300 g/L, 293 K.

joints. These metallographic specimens were polished without a scratch and then etched with the Hasson's reagent [17]. The composition of Hasson's reagent for metallographic specimens was displayed in Table 1. The macrostructures and microstructures were observed by OM (OLYMPUS DSX-510). Orientation information of distinct WZs from different joints was collected by SEM (Zeiss MERLIN Compact) with EBSD detector (Digiview 5). Before the EBSD experiments, the specimens were electropolished in a reagent of 90 mL CH_3OH and 10 mL H_2SO_4 at a voltage of 20 V together with the time of 10s. The typical step size was kept at 1 μm during the EBSD experiments. Precipitates were detected by TEM (JEOL-2100) and identified by selected area electron diffraction (SAED) patterns. The tensile tests were carried out at room temperature with the universal electronic material testing machine (Instron 2382) with a displacement velocity of 1 mm/min. The sample configuration of the tensile tests was given in Fig. 2. The fracture surface morphology of joints was observed by SEM (TESCAN VEGA II). The microhardness distributions of the different joints were collected by Vickers microhardness tester (HV-1000-DT) at the load of 200 g and dwelling time of 10s.

3. Results and discussion

3.1. Macrostructures and microstructures

A color etching technique based on the results of Hasson [17] was performed on distinct joints, and the color metallographs were displayed in Fig. 3. Macrostructures of joints welded at different welding speeds were collected by OM as displayed in Fig. 3(a-c). The weld width was decreased with the increasing welding speed. In addition, the grain coarsening was produced in the weld zone (WZ) due to the overheating of the molten pool [14]. The microstructures in various zones of the WZs were depicted in Fig. 3(d-f). The WZs consisted of coarse equiaxed grains and the grain sizes decreased with the increase of the welding speed. As the increase of the welding speed would decrease the welding heat input [18], the reduction of the grain size would be generated in the WZ with the increase of the welding speed. After the color etching, the sub-micrometer thick film was produced on the surface of the sample. The different colors and shadings of the grains were caused by the interference of light waves of different film thicknesses, which can represent distinct orientations in the WZs [17]. On account of the welding thermal cycle, the recrystallization was

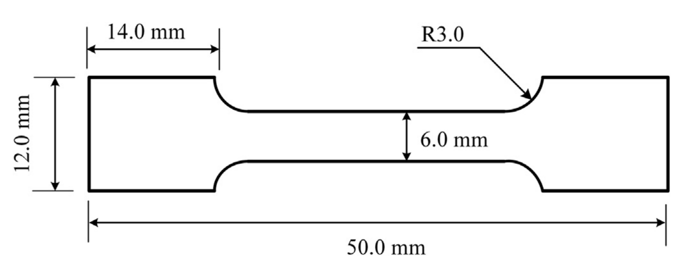

Fig. 2. Schematic diagram of the tensile sample.