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Effect of rhenium content on microstructures and mechanical properties of electron beam welded TZM alloy joints

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ABSTRACT

In order to strengthen weld zones of molybdenum-titanium-zirconium (TZM) alloy joints, electron beam welding experiments using rhenium (Re) addition into weld metals were conducted. The effect of Re content on the phase constitution, microstructural evolution, and mechanical properties of weld zone was investigated by optical microscope (OM), scanning electron microscope (SEM), electron backscattering diffraction (EBSD), transmission electron microscope (TEM), microhardness and tensile tests. Weld narrowing and grain refinement were produced in the welded TZM alloy joints by adding Re interlayers. Re-rich particles segregated in grain boundaries and led to the promotions of stress relaxation and cohesive forces of GBs. Besides, low-angle grain boundaries emerged and increased with Re contents in weld zones, which can hinder the initiations and expandings of microcracks. Consequently, the tensile strengths of the joints were enhanced with the increasing Re contents in weld zones. When the Re content in the weld zone reached 48.7 wt. %, the tensile strength of the joint can be up to 524 MPa and the fracture location was also transferred from weld zone to heat affected zone.

1. Introduction

With the development of aerospace and energy industries, molybdenum alloys have attracted increasing attentions due to their superior high-temperature mechanical properties [1–3]. The TZM (Mo-0.5Ti-0.08Zr-0.02C) alloy with a relatively higher recrystallization temperature than pure molybdenum, has been extensively used in industrial production [4–7]. Therefore, in order to meet the need of the practical application, different joining methods of TZM alloy have been given widespread attentions. In general, the fusion welding methods with relatively higher heat inputs are usually adopted to join TZM alloy. However, grain coarsening as well as intergranular fracture in the weld zone (WZ) often appeared after welding, which severely restricted its industrial application [8–10]. So far, the micro-alloying method has been adopted to solve these problems. Kohyama et al. [11] and Hiraoka et al. [12] illustrated that the tensile strengths of both base metal and welded joint increased with the carbon addition in the molybdenum alloy. When the content of carbon was controlled within a proper range, the carbide precipitates effectively improved the bonding strengths of grain boundaries (GBs) and increased the probability of the cleavage fracture in the WZs. Cockeram et al. [13] also found that the depletion of oxygen on GBs by boron addition in base metal led to the strengthening of the welded joint.

Besides elements C and B, Wang et al. [14] demonstrated that adding zirconium element into the electron beam weld can purify GBs in the weld zone. Even though the tensile strength of this joint was increased, the fracture was still produced in the weld zone. In attempt to further enhance the strengths of the joints, Re element was introduced into molybdenum and welding experiments of Mo-Re alloys were carried out in the past years. Tabernig et al. [8] found that the Mo-41Re alloy showed both superior ductility and tensile strength and its weldability was better than that of TZM alloy. Morito et al. [15] indicated that the bonding strengths of GBs in the WZs of the Mo-Re alloys with the addition of 25 wt.%–51 wt.% Re increased significantly with the increasing Re contents. However, the applications of Mo-Re alloys as base metal are restricted in many industrial productions due to their expensive costs [16]. To reduce the consumption of Re, Bryhan [17] tried to weld Mo-based alloy by GTA welding method with a Mo-Re filler metal. It was

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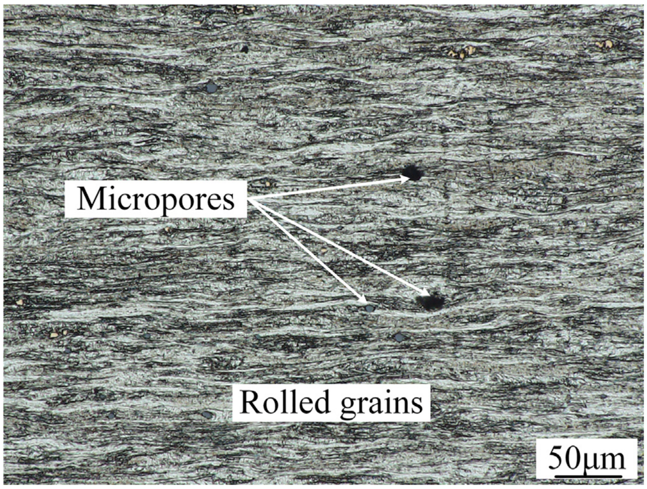

Fig. 1. Elongated grain structure of as-rolled TZM alloy.

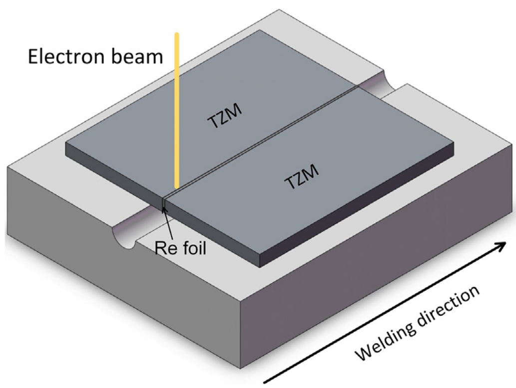

Fig. 2. Schematic diagram of EBW process with Re foil.

found that the tensile strength of the TZM alloy joint was remarkably enhanced and the fracture location was changed from WZ to HAZ. However, the strengthening mechanism of Re addition has not been clearly clarified.

In the present experiments, electron beam welding (EBW) was chosen to join TZM alloy on account of its high energy density and pure vacuum protection atmosphere [18]. Rhenium interlayers were adopted to study the effect of Re addition into the WZ on the microstructures and the mechanical properties of electron beam welded TZM joints. The macrostructures and microstructures of the joints were observed by an optical microscope (OM), scanning electron microscope (SEM) and electron backscattering diffraction (EBSD) and TEM in detail. The corresponding tensile strengths of welded joints at room temperature were evaluated and the fracture modes were also analyzed to investigate the strengthening mechanism of Re addition in the WZs.

2. Materials and experimental procedure

TZM plates (Mo-0.5Ti-0.08Zr-0.02C) fabricated by powder metallurgy were selected as base metals in the present study. The as-hot-rolled microstructure of the plate was depicted in Fig. 1. Rhenium foils with different thicknesses were chosen as the filler metals. TZM plates and Re foils were sanded by the abrasive papers to remove the oxide films and cleaned by the acetone for 5 min to remove stains before welding. TZM plates with a dimension of $100 \times 25 \times 3.0$ mm and Re foils with a thickness of 0.2 mm and 0.4 mm were clamped in an EBW equipment as demonstrated in Fig. 2. EBW experiments of TZM plates with and without Re foils were carried out, respectively, under a vacuum degree of 4×10^{-2} Pa, an accelerating voltage of 70 kV, a beam current of 35 mA and a welding speed of 350 mm/min. The contents of Re (W_{Re}) in WZs were controlled by changing the thicknesses of the Re foils and calculated by the following equation:

$$W_{Re} = \frac{A_1 \cdot \sigma_1}{A_1 \cdot \sigma_1 + (A_2 - A_1) \cdot \sigma_2}, \quad (1)$$

where A_1, σ_1, A_2, and σ_2 were the sectional area of the Re foil in the thickness direction, the density of rhenium, the area of WZ and the density of the TZM alloy, respectively. The areas of WZs of distinct joints were measured by an image processing software (Image Pro Plus) and the approximate contents of Re in WZs of different joints welded with Re foils of 0.2 mm and 0.4 mm were 21.6% and 48.7% in mass ratio.

The metallographic and tensile samples were sliced by wire-cut electric discharge machine perpendicular to the welding direction from the welded joints. Metallographic samples for OM and SEM were polished and etched with a reagent of 50 ml HNO_3, 30 ml H_2SO_4 and 30 ml H_2O. The metallographic samples for EBSD analysis were prepared by electropolishing 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 10 s. TEM samples were prepared by ion milling method. The macrostructures of distinct joints were observed by an optical microscope (OM, OLYMPUS DSX-510). The microstructures of different regions of the joints were observed by SEM (Zeiss MERLIN Compact) with an EBSD detector (Digiview 5). The typical step size was kept in 1 μm during the EBSD experiment. The weld zone of the joint welded with the addition of rhenium was observed by a transmission electron microscope (JEOL-2100). The microhardness distributions were measured by a Vickers microhardness tester (HV-1000-DT) under the load of 200 g and a dwell time of 10 s. The tensile strength tests were performed on a universal electronic material testing machine (Instron 2382) with the displacement velocity of 1 mm/min at room temperature. The configuration of the tensile sample for the tensile test was depicted in Fig. 3. The fracture surfaces of the joints were observed by SEM equipped with an energy dispersive spectroscopy (EDS).

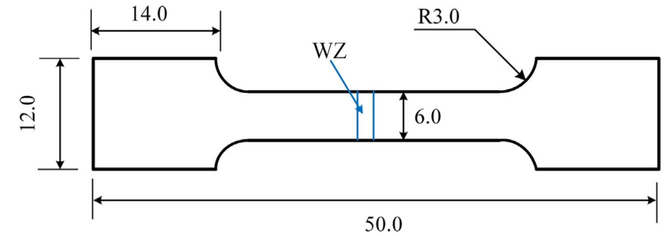

Fig. 3. Geometric configuration of the tensile sample.

3. Results and discussion

3.1. Macrostructures and microstructures

3.1.1. Grain morphologies and distributions

The macrostructures of welded joints with different contents of Re addition were observed, which were displayed in Fig. 4(a)–(c). Fig. 4(a)–(c) illustrated that the widths of distinct WZs showed significant differences with or without Re addition. Due to a higher melting point of Re than that of Mo element, the fusions of the WZ metals in the joints welded with Re interlayers absorbed more heat than that of the joint without Re interlayer during the welding process. Hence, narrower WZs were obtained in the joints welded with Re interlayers. The microstructures of various positions marked in Fig. 4(a)–(c) observed by SEM were shown in Fig. 4(d)–(i). Due to the overheating in the WZs, grain coarsening was induced in the