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Study on microstructure and performance of molybdenum joint welded by electron beam

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ABSTRACT

Electron beam welding of molybdenum was studied in this paper. The microstructures, mechanical properties and defects of the joints were analyzed. The results showed that the average hardness of the weld was 210 HV, while that of in heat affected zone was 202 HV, which was higher than base metal. The even tensile strength of the joints was 280 MPa, and the fracture position was located in the weld, which was brittle fracture. It were determined as quasi-cleavage fracture. Pore and crack defects were observed in the weld zone. The pores formed by the oxygen which was not escaping from the molten pool. Cracks were confirmed as solidification cracks and low plastic embrittlement cracks.

1. Introduction

Molybdenum has the advantages of excellent mechanical properties and thermal conductivity. Therefore, molybdenum has a wide application prospect in aerospace, machinery, chemical engineering, metallurgy, electronics and nuclear industries [1,2]. Molybdenum is characterised by good wear resistance and corrosion resistance, especially small thermal neutron capture area, which can be used as the structural material for the core of nuclear reactors. At present, the cladding materials of fuel rods are usually made by zirconium alloy. In contrast, molybdenum does not react with water, which can avoid zirconium water reaction and hydrogen explosion [3]. Therefore, there is a great significance to replace the zirconium by molybdenum, and the research of welding technology of molybdenum has become a top priority.

Wang T welded the molybdenum-titanium-zirconium (TZM) by electron beam, and the tensile strength of the joint decreased with the increase of the welding speed in a certain range. MoO_2 and TiO_2 precipitated at grain boundaries due to micro-segregation, resulting in a serious decrease of joint properties. By adding zirconium into the weld, ZrO_2 was formed preferentially in the interior of the grains, and the grain boundaries were purified to improve the tensile strength of the joint [4–6]. Welding TZM plate by friction stir welding, the strength of the joint was equal to that of the base material [7]. Through the diffusion welding of Mo-Cu with 10 μm thick Ni interface layer found the weak of joint in the Mo-Ni diffusion layer, and the maximum strength of the joint was 97 MPa [8]. Andrzej A welded molybdenum with vanadium, tantalum, nickel, titanium and copper by friction stir welding (FSW), determined the welding parameters [9]. The welding of molybdenum-rhenium (Mo-Re) alloys had also been studied. Cracks appeared at the interface of fusion zone after laser welding, and many large pores were observed. The diameter of the pores was about 15%–20% of the base plate thickness. Through the vacuum brazing of Ni-Cr-Si-B alloy brazing filler metal, a no defect joint was obtained, but there were CrB and $NiSi_2$ brittle phases in the weld [10,11]. Yazdanian welded the pure molybdenum plate by FSW which protected by argon gas. The joint was formed well and the heat affected zone (HAZ) was the weak zone. But there was still difficult for special shape workpieces [12]. Kolarikova welded pure molybdenum plate of 0.2 mm and 0.4 mm by EBW and GTAM. It was found that the HAZ of electron beam welding (EBW) was smaller and the grains size were smaller [13].

The research of molybdenum alloy welding is mainly focused on the welding of TZM plates, the welding of Mo-Re alloys and the welding of molybdenum alloy and other metals at present. The weldability of molybdenum is very poor. In the process of welding, the defects of pores and cracks are easy to appear and the joints have a lower strength. There are few studies on the welding of pure molybdenum. Although the joint can be obtained by FSW, there are many constraints. FSW is still difficult for the welding of curved materials. The stir head off the workpiece will form a hole at the end of the weld, which is difficult to repair. The stir head has a serious wear at the same time. Therefore, the fusion welding of pure molybdenum should be further explored. Compared with other welding methods, electron beam welding (EBW) has the advantages of high energy density, deep penetration, narrow weld seam, large depth to width ratio, small weld heat affected zone and so on [14]. Moreover, the high thermal conductivity

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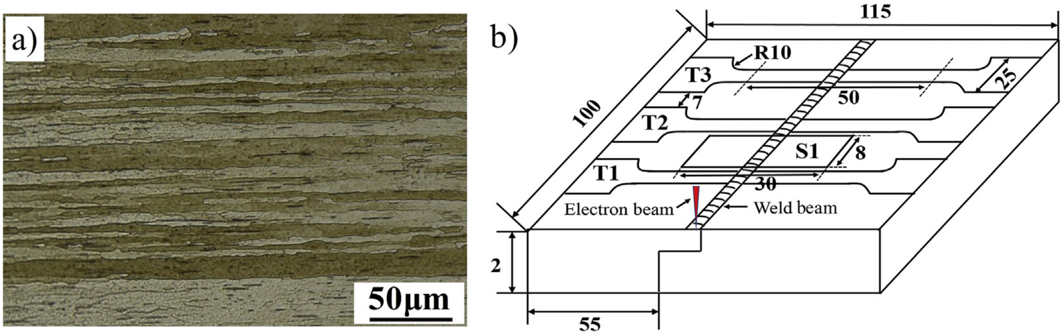

Fig. 1. A) Microstructure of molybdenum base material b) Sketch map of the welding.

of molybdenum, the obvious tendency of grains coarsening and embrittlement determine the great advantage of the EBW. On the one hand, EBW is in vacuum, which can effectively isolate the oxygen and nitrogen to the molten pool. On the other hand, the cooling rate of EBW is relatively fast, which can refine the microstructures and improve the mechanical properties of the joints. In this paper, the experiment of EBW of molybdenum was carried out to discuss the welding technology of molybdenum, analyzed the defects produced in the welding and the properties of the joint. Control the defects produced in the welding process.

2. Experiments

The base metal used in the experiment was molybdenum containing a small amount of La element (wt.5‰). Fig. 1a showed that the grains were elongated after the rolling process. The microstructure showed obvious rolling state and small La_2O_3 particles distributed on it. A proper amount of La dispersed in the microstructure could effectively refine the grains and increase the tensile strength of the base material [15]. The chemical composition of the material and the physical properties of the molybdenum were shown in Table 1 and Table 2 respectively. Lap joint was used in the test. The assembly diagram and size were shown in Fig. 1b, in which S1 was a specimen for microstructure analysis, while T1, T2 and T3 were used for tensile testing. The welding parameters were shown in Table 3.

The welding process was conducted in MEDARD45 EBW machine. The main performance indexes are as follows: maximum power is 6 kW, acceleration voltage is 20–60 kV, and it can be adjusted continuously. The welding beam is 0–100 mA. The vacuum degree of the electron beam gun can reach up to 5×10^{-4} Pa. The vacuum degree of the chamber used in this experiment was 5×10^{-2} Pa and it was carried out by the lower focus. The microstructure of the cross section was observed by ZEISS SUPRA 55 SAPPHIRE field emission scanning electron microscope (SEM), and the energy spectrum and fracture morphology were also analyzed in SEM. The tensile strength of base metal and joints were tested by AGX plus electronic universal testing machine at room temperature, the loading speed is 1 mm/min. And the microhardness distribution of the joint was measured by HXD1000 micro hardness tester. The pressure of the test was 200 N.

Table 1
Chemical composition of base material (wt.‰).

O	Si	Na	Cr	Ca	Co	Ni	La	Mo
0.4	0.03	0.02	0.02	0.02	1	0.02	5	rest

Table 2
Physical properties of molybdenum.

Density g/cm^3	Melting point Tm/K	Boiling point Tv/K	linear expansion 10^{-6}/K	Specific heat J/(g·K)	Thermal conductivity W/(m·K)
10.2	2896.15	5073.15	5.3	0.25	142

Table 3
Welding parameters.

Acceleration voltage U/kV	Focusing current I_f/mA	Beam I_b/mA	Welding speed v/(mm·min^{-1})
55	2480	16	180

3. Results and discussion

3.1. Microstructure analysis of welded joint

Fig. 2 was the SEM images of the microstructures in different parts of the joint. Fig. 2a showed the heat affected zone (HAZ) and weld zone (WZ) of the joint, and pores were found in the weld part. Fig. 2b was HAZ, the grains began to coarsening, no longer tended to the rolling direction, and the microstructure was uniform. Fig. 2c showed the molten zone, mainly consisted of coarse columnar grains. The orientation of the grains at the center of the weld was different from the weld near the fusion line. As can be seen from the diagram, the grains near the fusion line grew along the normal direction of the fusion line to the center of the weld. But the grains at the center of the weld grew along the vertical direction. There was a distinct misorientation between the two kinds of grain. And the boundary between the two grains can be clearly seen from the diagram. Because of the instantaneous melting of the metal in the weld under the high energy electron beam. When the electron beam penetrated the base material, the energy decreased with the increase of the depth, and the energy at the bottom of the weld was relatively small. Moreover, when the bottom of the weld was contacted with the welding fixture, the thermal conductivity of the metal fixture was much larger than that under the vacuum condition. The molten metal of the weld started to crystallize from the bottom to the top. At the same time, the molten metal near the fusion line was in contact with the base material, which also had a large conductivity. The metal crystallized in the direction of the maximum temperature gradient. The grains were formed as shown in the diagram.

The melting point of molybdenum is high and the thermal conductivity is large, which requires sufficient heat input to achieve penetration. So, it is necessary to ensure the penetration depth (i.e. heat input is not too small). But the excessive heat input will lead to the growth of grains, and the coarse grains led to the decrease of strength, plasticity and toughness, which affected the mechanical properties of joints.