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Fabrication of W/steel joint using hot isostatic pressing with Ti/Cu/Ti liquid forming interlayer

Wensheng Liu[1], Xinkuan Pang[1], Qingshan Cai*, Yunzhu Ma, Wentan Zhu

State Key Laboratory for Powder Metallurgy, Central South University, Changsha 410083, PR China

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ABSTRACT

Diffusion boning is a preferred method to join tungsten and steel for the manufacturing of some components in the fusion technology. However, solid state diffusion bonding encounters many limitations in producing the W–steel modules because it is not tolerant of joints of variable width, and moreover, its reliability is highly sensitive to surface cleanliness and roughness. Therefore, the use of liquid phase forming interlayer is required to eliminate the need for high surface cleanliness and low surface roughness to ensure good contact and diffusion between the bonded surfaces, overcome the large differences in the physical properties of W and steel. In this work, an innovative method is applied for bonding W to steel using Ti/Cu/Ti eutectic forming interlayer. W–steel joint circular sleeve is prepared by a hot isostatic pressing diffusion bonding method at 1050 °C for 1 h under 100 MPa pressure. The microstructural examination and mechanical properties evaluation of the joints show that the bonding of W to steel is successful. Investigations of the bonded specimens show a hard reaction layer containing TiC at the interface between Cu and steel, which can weaken the bonding interface.

1. Introduction

The targeted development of helium cooled high performance divertors for fusion DEMO reactors requires the selection and joining of tungsten (W) or W alloys and ferritic–martensitic high chromium steels in present design concepts [1]. The method for realizing such kind of connection is restricted by a lot of problems related to the large differences in the physical properties of both materials. For instance, fusion welding technique is inapplicable for joining of them, due to the large differences of their melting points. Furthermore, W and steel have significant differences in their coefficients of thermal expansion (CTE), which causes high thermally induced residual stress in W–steel joints after welding and/or subsequent exposing to mechanical and thermal load.

Until now several joining techniques including brazing [2–4] and solid state diffusion bonding [5–9] have been developed for the joining of W and steel. Brazing has been successfully used for joining of W–steel mock–up parts because brazes have the singular merit of being able to fill joints of irregular dimensions [10,11]. Although brazing alloys are metallurgically compatible with parent materials, the brazing temperature of 1150 °C is high enough to cause grain coarsening in steel (e.g., EUROFER97 [12]) and consequently leads to the degradation of material's properties. Thereafter, the upper working temperature of the assembly is also compromised by the presence of the lower–melting–point filler metal [11]. Diffusion bonding seems to be a suitable way to join W with steel due to its tolerable bonding temperature and the joint could be used at high temperatures. However, diffusion bonding tends to be limited as a production process because it is not tolerant of joints of variable width, moreover, its reliability is highly sensitive to surface cleanliness and roughness [13]. Shao et al. [14] reports that the diffusion bonded interface has lots of microvoids and cannot bear the load when the surfaces of the original specimens are rougher. To solve this problem, a liquid phase forming interlayer inserted between substrates is necessary to required to overcome the differences in their properties, and to eliminate the need for high surface cleanliness and low surface roughness to ensure good contact and diffusion between the bonding surfaces.

In this study, a hot isostatic pressing diffusion bonding technique was investigated as a method of joining W–steel joint circular sleeve using eutectic forming interlayer. The salient microstructural features associated with the interfacial region and its effects on the shear strength of the transition joint.

* Corresponding author.
E-mail addresses: caiqingshan@csu.edu.cn, cai2009pm@163.com (Q. Cai).
[1] These authors contributed equally to this work.

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2. Experimental procedure

2.1. Materials

The base materials used in this study are a high–Cr ferritic steel (Fe–17Cr–0.1C in wt.%, China TISCO) produced by mechanical alloying methods and commercially available W (99.95 wt.% purity, Xiamen Tungsten) obtained by powder metallurgy and forging along the radial direction. The interlayer materials in W/steel diffusion bonding experiments were Ti foil (99.9 wt.% purity, 20 μm thick) and Cu sheet (99.95 wt.% purity, 400 μm thick). Diffusion bonds were made between W and steel using Ti/Cu/Ti composite interlayer.

Ti/Cu/Ti composite interlayer was chosen for the following reason:

We have previously reported that the use of low yield strength and high ductility interlayer (e.g., Cu) is the most effective method of relaxing residual stress in W–steel joint [15]. According to the Ti–Cu phase diagram [16], a low melting point liquid–phase can be formed above 875 °C between Ti and Cu due to the eutectic reaction, as demonstrated by Hunt et al. [17]. Thus, the Ti/Cu/Ti combination as interlayer is proposed for diffusion bonding W to steel in this work. A liquid is formed at the bonding temperature resulting from the eutectic reaction between the core (Cu) and the outer (Ti) layer. When the Ti layer is very thin compared with the Cu layer in the joint, the liquid phase would occur at the joint interface at first, would decrease with time and finally disappear, since the liquid wets the surfaces of the base materials (W and steel) and interdiffuses with the core material (Cu) to transform into a more refractory solid material through re–solidification process.

2.2. Bonding procedure

For the hot isostatic pressing diffusion bonding of W and steel, W circular sleeve with dimensions of $30_{ID} \times 40_{OD} \times 75_{H}$ mm, and steel circular sleeve with dimensions of $41_{ID} \times 50_{OD} \times 75_{H}$ mm, were prepared using electrical discharge machining (EDM) and lathe processing. The joining surfaces of the W and steel circular sleeves were polished by grinder machining to a surface roughness R_a of about 1.2 μm. Then, the W and steel circular sleeves, Ti foil and Cu sheet were cleaned in an ultrasonic bath to remove the contaminators like oil and impurities on surfaces.

The prepared W and steel circular sleeves were assembled with the insertion of two Ti foils and a Cu sheet (Fig. 1), and encapsulated in the 304 stainless steel canisters with 2 mm in thickness. The canned materials were out–gassed at 450 °C for 3 h in a vacuum of less than 10^{-3} Pa for the hot isostatic pressing process. The hot isostatic pressing experiment was carried out at 1050 °C for 1 h under the pressure of 100 MPa. Then the canned materials furnace cooled to room temperature. 1050 °C was selected as the HIP temperature because it is the

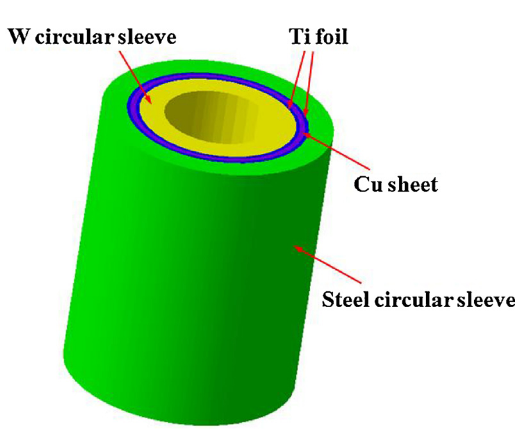

Fig. 1. Schematic representation of the sample assembly.

formation temperature of sufficient liquid phase for Ti–Cu diffusion couple according to our recent studies [18]. In addition, the joining temperature of W/steel divertor part should be controlled below 1050 °C in order to avoid grain coarsening and phase transition in steel [12,19].

2.3. Characterization technique

Fig. 2(a) was a W/steel joint circular sleeve diffusion bonded after removing the canning materials. For the microstructure and mechanical properties (hardness and shear tests) investigations, the bonded sample was cut by EDM into sub–size specimens. The microstructure and the chemical composition along the bond seams were analyzed using field–emission scanning electron microscope (SEM) and electron probe microanalysis (EPMA). The mechanical properties of the W/steel joint were evaluated by hardness and shear tests. The hardness near the bonding interface was determined by a nanohardness tester (VNHT) with a load of 5 mN. The joint strength test was performed at room temperature using a tensile testing machine (Instron–3369) at a crosshead speed of 1 mm/min with a specimen size of $4_L \times 4_W \times 8_T$ mm in a specially designed jig. The sectioning outline and the geometry of the shear test specimens are presented in Fig. 2(b) and (c), respectively. The interlayer was at the center of the gauge length. Fracture surfaces were observed in secondary electron mode of SEM combined with energy dispersive X–ray spectroscopy (EDS). The different phases on the fracture surface created during the bonding process were identified by means of X–ray diffraction (XRD) with Cu Kalpha radiation.

3. Results and discussion

The hot isostatic pressing diffusion bonded W/steel joint was successfully done using Ti/Cu/Ti liquid forming interlayer. The representative interfacial microstructure of the W/steel joint is given in Fig. 3. No unbounded regions and no micro–cracks could be found along the bond interfaces of W/Cu and Cu/steel. At high magnification of SEM–BSE in Fig. 3(b) and (c), the good metallurgic bonding is formed between the interlayer materials (Ti and Cu) and the substrates (W and steel), and two dark black reaction layers with different width are observed at W/Cu and Cu/steel interfaces. To investigate the elemental composition and its distance in the layers, elemental concentration profiles are measured across the bonded interfaces by means of EPMA. Fig. 4(a) shows such kind of mutual diffusion area at the interface of W/Cu with a thickness of ~1.8 μm. A similar area with a thickness of ~3.4 μm can be seen at the interface of Cu/steel in Fig. 4(b).

At the W/Cu interface, a thin diffusion zone (Reaction layer I) has been found close to the W base metal. It can be obviously recognized from the elemental concentration profiles that the Ti interlayer is disappeared because the peak of Ti concentration is analysed to be less than 10 at.%. In addition, intermetallic compounds were not detected in the diffusion zone due to the elemental concentration profiles composition changes gradually for W, Ti and Cu, which is different from a laminated structure of intermetallic compounds for Ti–Cu diffusion couple, as demonstrated by Hunt et al. [20]. The reason for this phenomenon may be due to the formation of partial transient liquid–phase at the W/Cu interface. According to the Ti–Cu binary phase diagram, the Ti–Cu liquid–phase would be formed between Ti and Cu at the bonding temperature of 1050 °C. The thin Ti interlayer and Ti–Cu intermetallic compounds would be consumed by the reaction of Cu–Ti liquid alloy with W substrate and Cu interlayer during the hot isostatic pressing diffusion bonding process. After bonding, the Ti interlayer disappears and forms a homogeneous solid solution with W and Cu.

As for the Cu/steel interface, similar to that observed for W/Cu interface, a dark black reaction layer (Reaction layer II) is also noted. EPMA analysis (Fig. 4b) reveals that there is no Ti interlayer residue at the Cu/steel interface. This result demonstrates that the inserted active Ti foil had been molten and consumed during the formation of the