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Microstructure and properties of W-Cu/CuCrZr/316L joint bonded by one-step HIP technique

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ABSTRACT

This work describes studies on the microstructure and properties of W-Cu/CuCrZr/316L joints bonded by one-step HIP technique. In the HIP process, both W-Cu/CuCrZr and CuCrZr/316L joints were connected simultaneously by diffusion bonding at 900 °C, 130 MPa for 2 h. Then for recovering the strength of CuCrZr alloy, heat-treatment process of solution annealing at 900 °C for 1 h which followed by water quench and aging treatment at 480 °C for 2 h were imposed on the HIPed module. After the heat treatment process, assessments on the microstructure, tensile test and Charpy impact test of the bonding joints were performed. Microstructural analysis showed that both the bonding joints were well welded and transition zones were observed along the interfaces of the joints. The microstructure of CuCrZr alloy was homogeneous with equiaxed grains and its mean grain size was around 42 μm. Mechanical test showed that the bonding strength of CuCrZr/316L joint was considerably high with an impact toughness value of 104 ± 2 J/cm^2.

1. Introduction

Hypervapotron is one of the most promising devices to remove heat fluxes up to 20–30 MW/m^2 in fusion reactors. The typical hypervapotron panel composes of a beryllium (Be) or tungsten (W) layer as an armor material, a copper alloy (CuCrZr) layer as a heat sink with cooling channels to enhance heat transfer and an authentic stainless steel (316L) as a structure material [1]. Generally, the referenced fabrication route of a hypervapotron panel consists of two hot isostatic pressing (HIP) processes. The first HIP process is done at 1030–1050 °C for 2 h to join CuCrZr alloy to a 316L plate. Due to the small cooling rate inside the HIP vessel, the bi-metallic CuCrZr/316L structure is submitted next to a solution annealing treatment at 980 °C for 30–60 min in another heat treating furnace and cooled as fast as possible by gas or water quench. The second HIP process is done at 560–580 °C for 2 h to join the Be or W layer on CuCrZr [2–4].

CuCrZr alloy is a precipitation hardening material and its microstructure and mechanical properties are strongly influenced by heat treatment process [5]. Usually, the high temperature in the first HIP process is beneficial for obtaining a high bonding strength of CuCrZr/316L joint. However, high HIP temperature may induce the strength of CuCrZr with a low Cr content close to 0.5 wt% decreases with large amounts of coarse precipitates and abnormal grains appeared [3]. For CuCrZr with a high Cr content close to 1.2 wt%, things are much more complex. Then the high temperature in the second HIP process, which is profitable to weld Be layer to CuCrZr alloy but always higher than the optimal aging temperature for CuCrZr alloy (470–480 °C), results in degradation of CuCrZr alloy properties once again. In order to improve the performance of CuCrZr alloy, the possibility that appropriately reducing the HIP temperature of the first process from 1040 to 1050 °C to 980 °C have been investigated in references [2,6–9]. However, results show that the abnormal grain growth of CuCrZr alloy is still a serious problem and especially on the large scale of industrial products [3].

Thus, for further reducing the negative influence of the high temperature on CuCrZr alloy, of the first HIP process and followed solution annealing treatment, a lower temperature of 900 °C was under consideration for both HIP and solution processes in this paper. Furthermore, in order to avoid the over-aging of CuCrZr alloy due to the second HIP process, armor materials and 316L were welded simultaneously to CuCrZr alloy by one-step HIP technique. Then heat treatment was applied to recovering the strength of CuCrZr alloy. Besides, nickel was electroplated on the materials of CuCrZr and 316L before they were welded by HIP. In order to investigate the effect of the one-step HIP technique on the properties of W-Cu/CuCrZr/316L joints,

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Table 1
Chemical composition of the materials of CuCrZr and 316L (wt.%).

CuCrZr	Cu	Cr	Zr	Impurities		
	Base	0.88	0.13	< 0.03		
316L	Fe	C	Mn	Si	P	S
	Base	0.028	1.88	0.35	0.014	0.005
	Cr	Ni	N	Nb	Co	Ti
	17.02	12	0.095	0.012	0.02	0.01

assessments on the microstructure, tensile test and Charpy impact test were performed in this study.

2. Experimental procedures

2.1. Materials and HIP procedures

The materials used in the W-Cu/CuCrZr/316L one-step HIP technique were W-Cu tiles (Cu coating was casting onto the W tiles at 1200 °C [10], W tiles dimensions were 40 × 12 × 2 mm with 1 mm thick pure Cu layer, the chemical purity of W was about 99.94%), CuCrZr alloy (the dimension was 120 × 60 × 7.2 mm) and commercial 316L stainless steel (the dimension was 120 × 60 × 12 mm), respectively. The chemical compositions of CuCrZr alloy and 316L are given in Table 1. The chemical compositions of CuCrZr and 316L were within the designated composition range of the ITER specification [11].

The whole experimental processes were as follows:

(1) Step 1: Electroplated by Ni

Firstly, the materials of CuCrZr and 316L plates were electroplated with a 6 μm-thick nickel coating by Watt's bath at 45 °C for 10 min.

(2) Step 2: One-step HIP process

Secondly, all plates were put into a 304SS container with a sandwiched structure of W-Cu/CuCrZr/316L (Fig. 1) and then they were sent to be HIPed (Actually, the structure was W/Cu/Ni/CuCrZr/Ni/316L, we omitted the interlayer and wrote it as W-Cu/CuCrZr/316L for simplicity). The HIP process was performed at 900 °C and 130 MPa for 2 h, followed by furnace cooling.

(3) Step3: Heat treatment process

Finally, the HIPed container was solution annealed at 900 °C for 1 h in another heat treating furnace and followed by water quench. Then, the solution annealed heat-treated container was aged at 480 °C for 2 h, followed by air cooling.

2.2. Experimental methods

After step 3, the microstructure observation of CuCrZr/316L and W-Cu/CuCrZr joints was carried out with an optical microscope and Field Emission Scanning Electron Microscopy (FE-SEM). The element distribution and chemical composition of various elements around the interface of CuCrZr/316L HIP joint were analyzed with an Energy Dispersive X-ray Spectrometry (EDS). Mechanical testing was just performed on the CuCrZr/316L joint. However, the W-Cu/CuCrZr/316L sample was too thin to cut tensile specimens at the direction perpendicular to the bonding interface, so another thicker 316L/CuCrZr/316L trimetallic sample for mechanical testing was obtained simultaneously in this study and then the specimens for tensile and impact test were cut from it as Fig. 2 shows. Tensile strength of CuCrZr/316L joint was evaluated at room temperature and the specimens were prepared according to Chinese GB/T228.1-2010 standard. The deformation rate of tensile speciments was 1 mm/min. Charpy Impact Tests were carried out using a 10 × 5 × 55 mm size specimen according to Chinese GB/T 229-2007.

3. Results and discussion

3.1. Microstructure

3.1.1. Microstructure of CuCrZr alloy

Fig. 3(a–c) shows the optical micrographs of CuCrZr alloy after different steps in the experimental processes. Fig. 3(a) shows the morphology of the as-received CuCrZr alloy of which the mean grain size was about 20 μm and the grains tend to be more or less aligned, elongated and parallel to the rolling direction. Fig. 3(b) shows the morphology of CuCrZr alloy after step 2. It can be seen that the grains of CuCrZr alloy grew up slightly and the mean grain size was in the range of 35–45 μm. Besides, the number of elongated grains declined sharply and the grains were nearly equiaxed. Fig. 3(c) shows the morphology of CuCrZr alloy after step 3. Results show that solution annealing at 900 °C for 1 h and aging at 480 °C for 2 h make the grains more uniform. Comparing with step 2, the mean grain size of CuCrZr alloy was not further increased but high quantity of annealing twins were observed after solution annealing.

In conclusion, after the whole one-step experimental processes, the mean grain size of CuCrZr alloy was around 42 μm and it was still far smaller than 100 μm which was the upper limit that required in ITER documents. The microstructure of CuCrZr alloy was homogeneous with equiaxed grains and no abnormal grain size could be observed.

3.1.2. Microstructure of CuCrZr/316L joint

In Fig. 4, the optical micrographs of CuCrZr/316L HIP joint with Ni interlayer after step 3 are presented. No macro-pores or cracks were observed at the interface. Interestingly, a transition zone with a width of more than 20 μm was obtained at CuCrZr side along the bonding interface. The color of the zone is lighter than CuCrZr matrix and the grain boundaries in this zone become blurred. The phenomenon may be caused by the formation of Cu-Ni α-phase solid solution, which leaded to failure in etching the grains by the initial etchant.

In order to get more details about the transition zone and the bonding interface, the microstructure of CuCrZr/316L interfaces was observed by SEM. Surprisingly, the transition zone was divided into two parts as zone 1 and zone 2, as shown in Fig. 5(a, b). Results of EDS line-scan across the bonding interface were shown in Fig. 5(c). By comparing Fig. 5(b) and (c), it can be found that zone 1 was the sublayer of CuCrZr matrix and zone 2 was the Ni interlayer. Because Cu and Ni can form infinite solid solution, diffusion was easily occurred between the

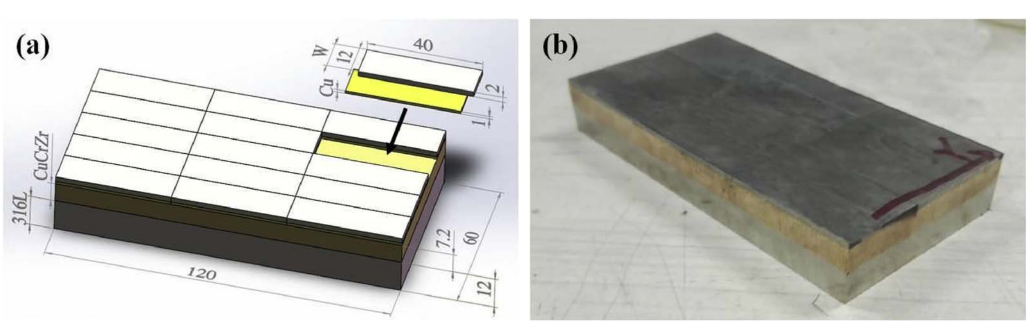

Fig. 1. (a) The sketch drawing of W-Cu/CuCrZr/316L structure; (b) the picture of the actual object.