Diffusion welding of 93W alloy to OFC and structural control of 93W/OFC joint

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In the research fields of astrophysics, geophysics and inertial confinement nuclear fusion etc, high pressures over 10^5 MPa are necessary to studying equation-of-state and dynamic properties of materials [1–3]. Such dynamic pressures can be generated via a new kind of functionally graded material [4] called "flier-plate material with graded impedance" [5–9]. Due to the high wave impedance and impedance variation range as well as good mechanical properties, 93W alloy (containing 93 wt% tungsten with nickel and iron as the additives) and OFC (Oxygen-Free-Copper with a purity higher than 99.95%) are chosen as the composite system of the flier-plate material [10–12]. How to join 93W to OFC and ensure the interfacial flatness of the 93W/OFC joint is the main precondition for the preparation of the flier-plate material with graded impedance.

As we know, tungsten (W) and copper (Cu) joints have been used for a variety of electrode components including key components of heavy-current plasma arc electrodes, and have also been employed as the cooling structure of X-ray tubes, because of the high thermal resistance of W and good thermal conductivity of Cu. However, due to the distinctive differences in properties especially the melting temperature, W and Cu are usually difficult to join by the traditional methods, and diffusion welding, friction welding or sliver brazing are possible ones [13–15]. But these methods are mainly focused on the properties of the W/Cu joints in order to improve the strength, whereas the structural control, especially the interfacial flatness of the joints, is not reported. Moreover, the mechanism of the bonding is few discussed. Therefore, in the present study a diffusion welding method is employed to join 93W to OFC. The mechanism of the bonding of 93W to OFC and the structural control of the welded 93W/OFC joint are investigated.

In diffusion welding, temperature, pressure and time are the three main parameters which must be well controlled to obtain a high-quality joint. Table I lists different parameters for diffusion welding of 93W to OFC and the corresponding outcomes of the joints. From this Table, we can see that the welding temperature plays the most important role among the three parameters, deciding both the occurrence of welding and its extent. When the welding temperature is lower than 1073 K, 93W and OFC are hard to weld because the reaction between W and Cu atoms is not adequate. Conversely, if too high temperatures (>1123 K) are employed, OFC which has a low strength is easily deformed under the welding pressure, although 93W and OFC can be joined. As a result, the interfacial flatness of the 93W/OFC joint is severely damaged. Therefore, only over a rational temperature range (about 1073–1123 K) could firmly welded 93W/OFC joint, without large distortion or damage, be obtained.

Fig. 1 shows the secondary electron image of the 93W/OFC joint diffusion welded at 1073 K. The left side of the interface is OFC-plate and the right side is 93W alloy. Since 93W is a biphase alloy consisting of tungsten-grains and nickel-iron-binder, it might be considered that the welding of 93W to OFC is via two mechanisms: the bonding of OFC to tungsten-grains and that of OFC to nickel-iron-binder.

The microstructure of the interface of OFC/tungsten-grains and the corresponding line distributions of elemental W and Cu across the interface are shown in Fig. 2. It can be seen that a thin W-Cu transition layer, which is merely a few micrometers in thickness, is formed in the OFC-plate close to the interface. As we know the welding of OFC/tungsten-grains is typical solid-state bonding, which accords with the traditional three-stage theory for the bonding process [16]. Firstly, under the applied pressures OFC-plate comes into contact with tungsten-grains by the plastic deformation, so that physical or weak-chemical actions occur. Secondly, the heat-vibrations of W and Cu atoms become violent with the increasing of the welding temperature and they begin to combine with each other after acquiring enough energy. Subsequently, W atoms go across the interface into the OFC-plate and a layer of W-Cu transition, in which the content of W and Cu changes gradually, is finally formed. According to the diffusion welding of different metallic materials, some thick transition layers or new phases are usually produced at the joined interface, which results from the further elemental diffusion in the third stage of the bonding process. However, neither solid-solution nor reaction can take place between W and Cu, thus the welding of OFC to tungsten-grains will finish just after the first and second stage bonding without the third stage of elemental diffusion.

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TABLE I Parameters for diffusion welding of 93W to OFC and the outcomes of the joints

Parameters			
Temperature	Pressure	Time (min)	Results
1023	5	20	A
1023	15	30	A
1073	5	20	B
1073	10	10	B
1073	10	20	B
1123	10	20	B
1173	15	20	C
1223	15	20	C

A—not welded; B—well welded; C—OFC was deformed.

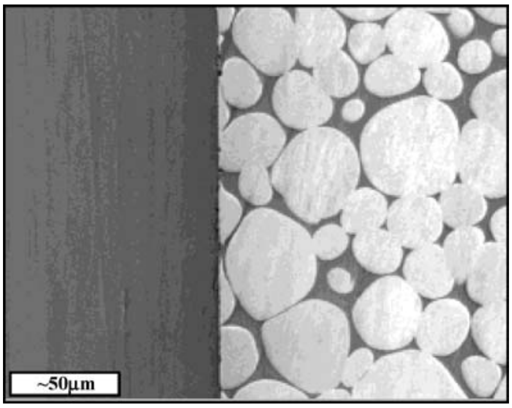

Figure 1 Secondary electron image of 93W/OFC joint diffusion welded at 1073 K-10 MPa-10 min (the right side of the interface is 93W alloy).

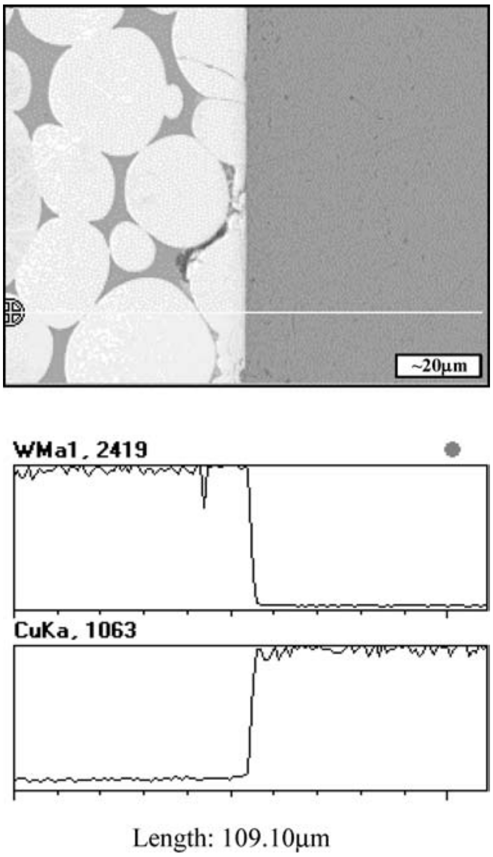

Figure 2 Joined interface of OFC/tungsten-grain and line distributions of elements W, Cu.

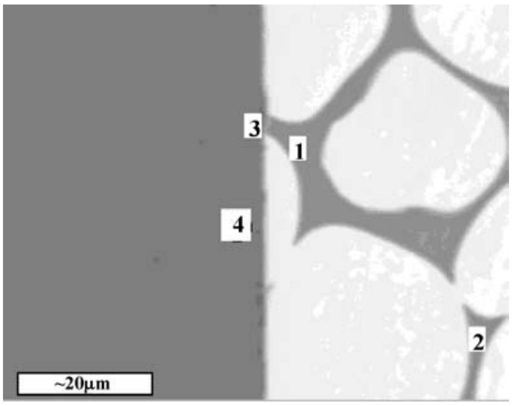

Figure 3 Joined interface of OFC/nickel-iron-binder (the left side is OFC).

Fig. 3 shows the joined interface of OFC/nickel-iron-binder. The compositions of four spots in the OFC-plate and nickel-iron-binder are quantitatively analyzed and the results are listed in Table II. In Fig. 3, 1 and 2 are two spots in the nickel-iron-binder which are near and far from the interface respectively, while spots 3 and 4 are in the OFC-plate which are in contact with nickel-iron-binder and tungsten-grains separately. It can be seen that some elemental copper appears in the nickel-iron-binder which are adjacent to the OFC-plate (for example, spot 1) as contrasted to spot 2. And from the compositions of spots 3 and 4, we can also find elemental nickel and iron in the OFC-plate which is in contact with the nickel-iron-binder. All these shows that the diffusion of elemental copper, nickel and iron through the interface of OFC/nickel-iron-binder takes place, which accomplishes the welding of OFC to nickel-iron-binder.

From the above analysis, it can be concluded that the diffusion welding of 93W to OFC is attributed to two mechanisms: the bonding of OFC to tungsten-grains and the bonding of OFC to nickel-iron-binder. Since these two mechanisms are both mainly affected by the welding temperature, that is, the higher the temperature, the more effective the mechanisms, the 93W/OFC joint can be welded more firmly with the increasing of the temperature.

On the other hand, the properties of 93W and OFC, especially the coefficients of thermal expansion which are 4.5×10^{-6}/K and 16.7×10^{-6}/K respectively at room temperature, are different from each other. As a result, the residual thermal stresses and stress-induced distortions [17, 18] might be produced simultaneously during the heating and cooling process, which will unavoidably affect the interfacial flatness of the welded 93W/OFC joint or even destroy it. The residual thermal

TABLE II Compositions of the four spots shown in Fig. 3

	Main compositions (mol%)			
Spots	W	Cu	Ni	Fe
1	8.31	0.53	60.60	26.02
2	9.48	–	60.15	25.72
3	0.25	98.94	0.51	0.27
4	0.28	99.40	–	–

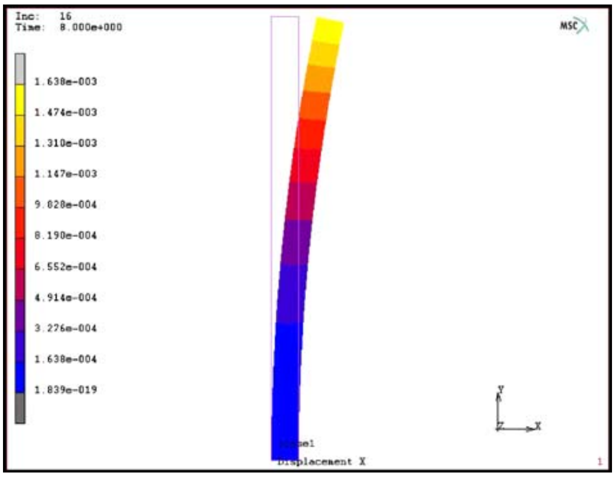

Figure 4 Distribution of displacement in the 93W/OFC joint (the left side is 93W alloy and the welding temperature is 1073 K).

stresses in the 93W/OFC joint when it cools from the welding temperature 1073 K to room temperature are then calculated by a finite element method (FEM) [19]. One fourth part of an axisymmetric model, which is composed of 7200 elements and 7421 nodal points, is used for the FEM calculation and it is assumed that no external axial load is applied to the joint. The distribution of the displacement in the joint resulting from the stresses is shown in Fig. 4. We can see that severe distortion takes place in the 93W/OFC joint and the FEM calculation further shows that a pressure of about 7 MPa is adequate to ensure the interfacial flatness the joint.

As mentioned above, the interfacial flatness of the welded joint is the basis for preparing high-quality flier-plate material with graded impedance, so the structure of the 93W/OFC joint must be well controlled besides the precise machining (including cutting, grinding and polishing, etc.) of 93W and OFC prior to the welding. For the above reasons, two methods are then employed to control the structure of the 93W/OFC joint. Firstly, we fix the 93W/OFC assembly in a rigid mould (a graphite mould is used in this work). At the same time, an adequate restrictive pressure (10 MPa) is exerted to resist the stress-induced deformation until the welded joint cools to room temperature. Secondly, the heating and cooling rates are also well controlled, so that the residual stresses and stress-induced deformation in the 93W/OFC joint can be reduced as much as possible.

By employing the above diffusion welding parameters and structural control techniques, a 93W/OFC joint with flat interface is successfully obtained as shown in Fig. 1, which meets the basic structural requirements of the flier-plate material with graded impedance.

In conclusion, a diffusion welding method was employed to join 93W to OFC and firmly welded 93W/OFC joint without large distortion or damage was obtained over a temperature range of 1073–1123 K. The mechanism analysis showed that the welding of 93W to OFC could be attributed to the bonding of OFC to tungsten-grains and the bonding of OFC to nickel-iron-binder mainly by elemental diffusion. And by exerting restrictive pressure, controlling heating and cooling rates etc, the interfacial flatness of the welded 93W/OFC joint was well controlled.

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