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Journal of Nuclear Materials 307–311 (2002) 1542–1546

journal of nuclear materials

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Mechanical properties of HIP bonded W and Cu-alloys joint for plasma facing components

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Abstract

Hot isostatic pressing (HIP) bonding technology of W (tungsten) and Cu-alloys have been developed to fabricate plasma facing components of the fusion reactor. As regards W and oxygen free high conductivity copper (OFHC-Cu), the highest bonding strength was achieved at the HIP condition of 1273 K × 2 h × 147 MPa. On the other hand, W and dispersion strengthened copper (DS-Cu) were not bonded directly because of tungsten oxide production at the bonding interface. In this study, HIP bonding tests on W and DS-Cu with OFHC-Cu disk and/or Au-foil were performed. Bonding tests with OFHC-Cu disk were successfully bonded and it is shown that thickness of OFHC-Cu disk over 1.0 mm may be needed and the tensile strength are a little higher than that of HIP treated OFHC-Cu. Bonding tests with Au-foil were also performed and successfully bonded. Au-foil lead to an improvement in bonding strength and a lowering of bonding temperature.
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1. Introduction

W (tungsten)-alloys are considered as plasma facing material (PFM) for fusion reactor because of many favorable properties such as high melting point (3655 K), high thermal conductivity, and so on [1,2]. Copper and Cu-alloys (e.g. oxygen free high conductivity copper (OFHC-Cu) and dispersion strengthened copper (DS-Cu)), have been proposed as heat sink materials behind the PFM due to their high thermal conductivity [1,3,4]. Plasma facing components (PFC) are designed as the duplex structure where W armor tiles are bonded onto Cu-alloy heat sink [5]. In order to fabricate PFC, it is required to develop reliable bonding techniques [6]. We started the bonding technology development by hot isostatic pressing (HIP) method between W and Cu-alloys. HIP method has advantages of good sizing precision and large-scale application [7]. As we have reported earlier [8], the highest bonding strength for W and OFHC-Cu was achieved at the HIP condition of 1273 K × 2 h × 147 MPa. On the other hand, W and DS-Cu were not bonded directly because of tungsten oxide production at the bonding interface and residual stress. In this study, HIP bonding tests on W and DS-Cu with OFHC-Cu disk were performed. It was expected that the OFHC-Cu disk will prevent tungsten oxide production and will relax residual stresses at the interface.

HIP bonding tests with W and Au-foil [9] were also performed. According to the phase diagram, W–Cu system is insoluble perfectly. Whereas Au is easily soluble in Cu and Au–W system is a complete solid solution. Au-foil will lead to an improvement in bonding strength and a lowering of bonding temperature.

2. Experimental

2.1. Materials

The W used in the present experiments was manufactured by powder sintering method (Tokyo Tungsten

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PII: S0022-3115(02)01169-8

Table 1
Chemical composition of tested materials (ppm)

	W	Al	Li	Na	Mg	Fe	Si	Co	
Tungsten	Balance	<2	<50	<1	<1	10	<5	<0.48	
	Cu	Al	B	Pb	Fe				
OFHC-Cu	99.99 (wt%)	–	–	–	–				
DS-Cu (GlidCop AL25)	Balance	2500	170	7	13				
	Au	Ag	Cu	Fe	Pd	Pt	Zn	Cd	Pb
Au	Balance	2	2	6	5	20	2	0.1	0.1

Table 2
Tested HIP conditions and results of bonding tests

	HIP conditions	Thickness of OFHC-Cu (mm)	Results	Oxide	Cracks
W/DS-Cu	1173–1323 K, 147 MPa, 2 h	–	×	Yes	Yes
W/OFHC-Cu/DS-Cu	1273 K, 147 MPa, 2 h	0.1	×	No	No
	1273 K, 147 MPa, 2 h	0.3	◯	No	No
	1273 K, 147 MPa, 2 h	0.5	◯	No	No
	1273 K, 147 MPa, 2 h	1.0	◯	No	No
	1273 K, 147 MPa, 2 h	1.4	◯	No	No
	1273 K, 147 MPa, 2 h	1.8	◯	No	No
W/Au/OFHC-Cu/DS	1123 K, 147 MPa, 2 h	1.0	◯	No	No
W/Au/OFHC-Cu/Au/DS	1123 K, 147 MPa, 2 h	1.0	◯	No	No

(×) Not bonded, (◯) successfully bonded.

Co. Ltd.). OFHC-Cu (Hitachi Electric Cable Co. Ltd.) and DS-Cu (GlidCop Al-25) were selected as pure Cu and Cu-alloy respectively. The thickness of Au-foil (Nilaco Co. Ltd.) was about 40 μm. The chemical compositions are listed in Table 1. The materials were cut into cylindrical shape samples of 20 mm diameter and 20 mm height. The surface roughness of the samples was measured by a laser microscope. It was found to be about 0.5 μm R_a for W and about 0.3 μm R_a for Cu-alloys. The samples were vacuum-sealed in a low carbon steel capsule by electron beam welding.

2.2. HIP bonding tests

HIP bonding tests were performed using 'Dr HIP' (KOBELCO Co. Ltd.). The HIP conditions were 1273 K × 2 h × 147 MPa for W/DS-Cu and W/OFHC-Cu/DS-Cu. The condition is similar to the optimum HIP condition for W/OFHC-Cu [8]. Whereas bonding tests with Au-foil were performed at 1123 K × 2 h × 147 MPa to avoid melting of Au–Cu alloy. The HIP conditions are listed in Table 2. High purity argon was used as pressurizing gas.

2.3. Evaluation of the bonded specimens

The HIP bonded specimens were machined to prepare specimens for metallographic observations and specimens for tensile tests. The metallographic specimens were mechanically polished and chemically etched for optical and SEM/EPMA observations. The test pieces for tensile test were sheet-like as shown in Fig. 1. The tests were performed at RT, 473, 673 and 873 K in a vacuum of less than 2.0×10^{-2} Pa. The crosshead speed was 0.5 mm/min.

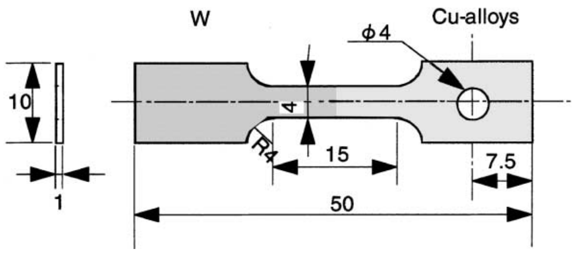

Fig. 1. Test piece for tensile tests (unit: mm).

3. Results and discussion

3.1. Results of bonding tests on W/DS-Cu with OFHC-Cu disks

The results of bonding tests on W/DS-Cu are shown in Table 2. W/ DS-Cu were not bonded directly. Fig. 2 shows a SEM micrograph of the bonding interface of W/ DS-Cu. There are tungsten oxide and some cracks at the bonding interface. Probably, DS-Cu includes some oxygen in the production process. Bonding tests on W/DS-Cu with 0.3–1.8 mm thickness OFHC-Cu disks were successfully bonded. Fig. 3 shows a SEM micrograph of the bonding interface of W/DS-Cu. No tungsten oxide and no cracks were observed at the bonding interface.

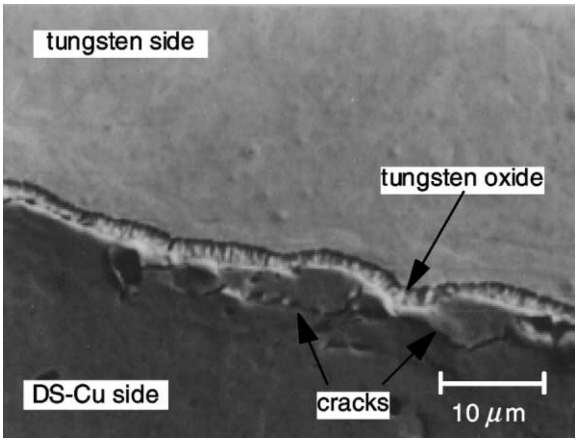

Fig. 2. SEM photograph of bonding interface between W and DS-Cu.

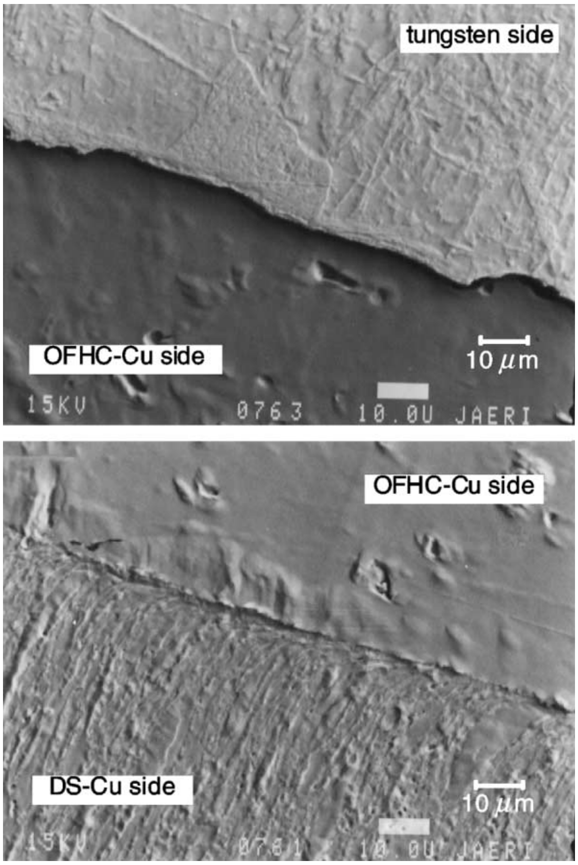

Fig. 3. SEM photographs of bonding interface between W and DS-Cu with 1.0 mm OFHC-Cu disk.

Table 3
Results of tensile tests on bonded W and Cu-alloys

	Test temperature (K)	Tensile strength (MPa)	Fracture location
W/OFHC-Cu [8]	RT	140, 129	W crack, interface W side
	473	123, 129	Interface W side, OF side
	673	86, 74	W/OF, W/OF
	873	31, 32	W/OF, OF side
W/OFHC-Cu/DS-Cu	RT	186, 186	Interface W side, OF/DS
	473	151, 124	OF/DS, OF/DS
	673	94, 94	OF/DS, OF/DS
	873	37, 49	OF/DS, OF/DS
W/Au/OFHC-Cu/DS	RT	128	W/OF interface W side
	473	139	W/OF interface W side
	673	98, 82	W/OF, W/OF
	873	32, 54	W/OF, W/OF
W/Au/OFHC-Cu/Au/DS	RT	127	W/OF interface W side
	473	147	W/OF interface W side
	673	87, 90	W/OF, W/OF
	873	38, 48	W/OF, W/OF

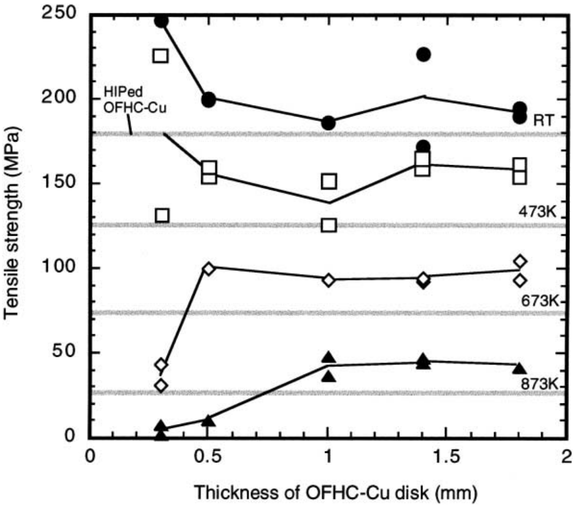

Fig. 4. Results of tensile tests on W and DS-Cu with OFHC-Cu disk and HIPed OFHC-Cu at corresponding temperatures.

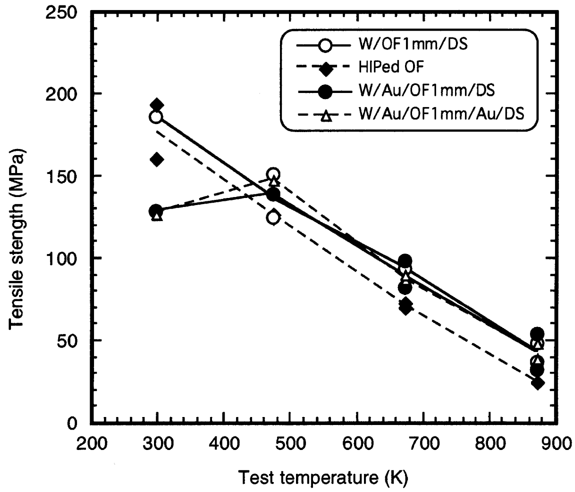

Fig. 5. Results of tensile tests on W and DS-Cu with OFHC-Cu disk and Au-foil.

However, with 0.1 mm thick OFHC-Cu disk bonding did not occur. Maybe because the residual stresses were not relaxed.

The results of tensile tests of bonded samples are summarized in Table 3. Fig. 4 shows the results of tensile tests with various thickness of OFHC-Cu disk. At low temperatures, the tensile strengths with 0.3 and 0.5 mm thickness were higher than those with thicker disks. However, at elevated temperatures the tensile strengths with thin disks were lower than that with the thicker disks. It is shown that thickness of OFHC-Cu insert over 1.0 mm may be needed and the tensile strengths are a little higher than those of HIP treated OFHC-Cu. Many specimens were fractured at OFHC-Cu/DS-Cu interface, since a necking occurs at the location.

3.2. Results of bonding tests on W/DS-Cu with Au-foils

The results of bonding tests with 1.0 mm OFHC-Cu disk and Au-foils are shown in Table 2. Bonding tests with Au-foil were also successfully bonded. No tungsten oxide and no cracks were observed at the bonding interface. The results of tensile tests of bonded samples are summarized in Table 3. Fig. 5 shows the results of tensile tests on the bonded W/Cu and HIPed OFHC-Cu. It is clear that the bonded specimens with and without Au-foil had almost the same strength at temperatures from 473 to 873 K. In this temperature range, the specimens with Au-foil fractured at the interface of W and OFHC-Cu. Whereas, those specimens tested at RT were a little weaker than those without Au-foil and they fractured on the tungsten side and near the bonding interface. The surface of tungsten might be weakened during the machining process and the weakened area might influence the residual stresses [8].

4. Conclusion

The results obtained in this study can be summarized as follows:

1. W/DS-Cu were not bonded directly because of tungsten oxide production at the bonding interface and residual stress. W/DS-Cu with OFHC-Cu disks of thickness over 0.3 mm were successfully bonded.
2. Results of tensile tests suggest that a thickness of OFHC-Cu insert over 1.0 mm may be needed to bond W and DS-Cu. The tensile strengths are a little higher than that of HIP treated OFHC-Cu.
3. Bonding tests with Au-foil were also successful. The tensile strengths were almost the same order of magnitude as those of without Au-foil at temperatures from 473 to 873 K.
4. It was found that Au-foil may lead to a lowering of bonding temperature.

Acknowledgements

We greatly appreciate the support by the members of NBI heating laboratory, JAERI-Naka during this study. We also greatly appreciate the helpful comments given by Dr M. Akiba and the members of blanket engineering laboratory, JAERI-Naka.

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