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High heat flux testing of tungsten plasma facing materials

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Abstract

Both tungsten with a microstructure of ultra-fine grain size (sub-micron grain size) and functionally graded W/Cu materials have been fabricated by a newly developed technology named resistance sintering under ultra-high pressure. It is found that when decreasing the grain size of tungsten (from 7 μm to 0.5 μm), the micro-hardness and bend strength of tungsten will increase significantly. Thermal shock resistance by water quenching shows that the concept of functionally graded materials is effective at reducing the thermal stress between tungsten and copper. High heat flux testing using a laser beam shows that tungsten with sub-micron grain size can endure a higher heat load than that of tungsten with a grain size of larger than 1 μm, and functionally graded W/Cu materials can endure a higher heat load than that of pure tungsten.

1. Introduction

Divertor materials for the next fusion reactor devices, such as International Thermonuclear Experimental Reactor (ITER), will face severe problems such as thermal shock fracture, surface erosion due to sublimation, and very high heat load. Tungsten is considered as one of the most promising plasma facing materials (PFMs) for the divertor of a fusion reactor because of many favorable properties, such as high melting point, excellent erosion resistance, etc. [1–4]. When used as a divertor material, tungsten also has to be bonded onto a cooled substrate made of a copper-based alloy, which can withstand the high heat load on the divertor plate.

However, using tungsten as a divertor material has two main technological difficulties that need to be overcome. One of the disadvantages of tungsten is related to its brittle nature at room temperature and high DBTT (ductile to brittle transition temperature) due to its body-centered-cubic lattice. One solution to this problem is the fabrication of tungsten with ultra-fine grain size. The other main technological disadvantage of tungsten is the difficulty in joining tungsten effectively to a copper-based heat sink. Because the coefficient of thermal expansion and elastic modulus between tungsten and copper are very different ($\alpha_{Cu} \approx 4\alpha_{W}$, $E_{Cu} \approx 0.2E_{W}$), this will lead to high thermal stresses during operation and even damage of the W–Cu joint. To solve this problem, the concept of a functionally graded material (FGM) has been used to join tungsten to copper as PFMs [5–8]. Due to the large difference in melting point between W and Cu (about 2100 K) and no overlap of sintering temperature ranges, it is not

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easy to fabricate W/Cu FGM by conventional methods.

A newly developed method called resistance sintering under ultra-high pressure has been invented in the authors' Lab for fabrication of W/Cu FGM [9]; it is also a good technology to fabricate pure tungsten with ultra-fine grain size [10]. The objective of this study is the development of tungsten with a microstructure of fine grain size and W/Cu FGM.

2. Experiments

For fabrication of tungsten with different grain size, W powders with an average particle size of 0.5 μm, 1 μm and 7 μm and purity of >99.5% were used as the starting materials.

For fabrication of a W/Cu FGM, W powder with particle size of 1 μm and Cu powder with particle size of <74 μm and purity of >99% were used as the starting materials.

A special experimental setup described in Ref. [9,10] was employed to fabricate both the tungsten with fine grain size and the W/Cu FGM. This fabrication method was named resistance sintering under ultra-high pressure (RSUHP). The pressure (about 5 GPa) was isostatically applied to a green compact to avoid pressure gradients, which may cause segregation of Cu and abnormal grain growth of W [11]. An alternating current (AC) was then applied to the sample, and the sample was heated mainly by Joule heat. The sintering time was only 1 min. The size of all samples was a cylinder with a diameter of 20 mm and a length of 10 mm.

SEM has been used to observe the microstructure. Some properties, such as micro-hardness and the bend strength of tungsten with different grains size have been obtained. The thermal shock resistance was test by water quenching. High heat flux testing was carried out using a pulsed laser beam heating apparatus.

3. Results and discussion

3.1. Tungsten with ultra-fine grain size

One of the best advantages of RSUHP was that a very short sintering time (about 1 min) was sufficient, thus almost no grain growth could occur during sintering.

Fig. 1 shows the micrograph of W powder with average particle size of 0.5 μm and a specimen after sintering. Table 1 lists the density, the micro-hardness and the bend strength of tungsten with different grain size. It can be seen that tungsten with very high density was fabricated by RSUHP. As the grain size of tungsten decreased, its micro-hardness and bend strength increased significantly.

3.2. W/Cu FGM

Fig. 2 is a backscattering image of the cross section of a six-layer W/Cu FGM. A well graded compositional transition was found. This reveals that there was no obvious composition migration during the very short sintering time. For comparison, a W–Cu laminated sample was also fabricated by the same method – RSUHP.

3.3. Thermal shock test

A preliminary thermal shock test was conducted using a muffle furnace. Samples were put into the

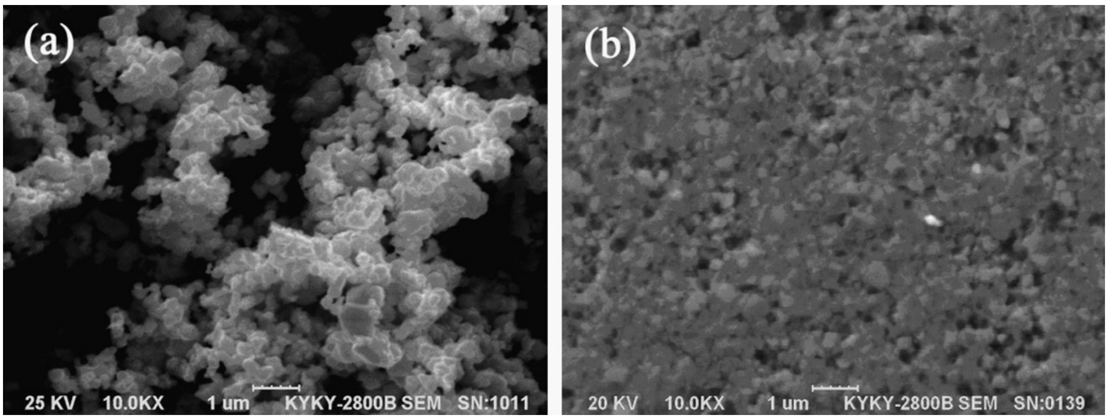

Fig. 1. SEM micrograph of tungsten powder with 0.5 μm particle size and its appearance after sintering: (a) tungsten powder and (b) specimen after sintering.

Table 1
Properties of tungsten with different grain size

Property	Sample A	Sample B	Sample C
W powder size (μm)	0.5	1	7
Relative density (%)	95.65	97.49	98.40
Micro-hardness (HV)	989.92	772.30	592.20
Bend strength (MPa)	597.29	561.12	483.21

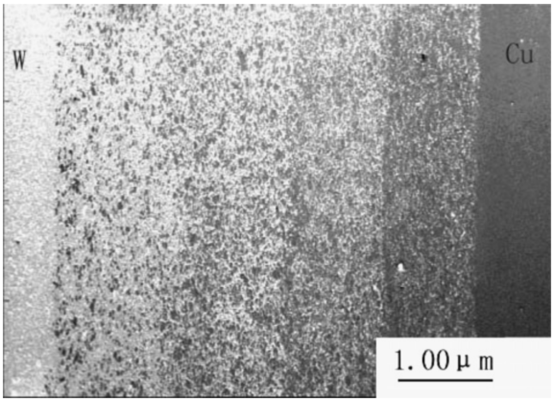

Fig. 2. SEM micrograph of cross section of six-layer W/Cu FGM, the copper content for each layer are: 0%, 20%, 40%, 60%, 80% and 100%.

furnace and held at 800 °C for 3 min. After heating, the samples were directly quenched into water. The temperature of the water throughout the cycling was between 20 and 30 °C.

No damage occurred in the tungsten with different grain size, but obvious oxidation occurred after 30 quenching cycles.

In the W–Cu laminated sample, many vertical cracks could be observed in the W part and detachment occurred at the interface between W and Cu after 10 quenching cycles. After 15 quenches, the W layer was broken to pieces and peeled off. In the case of W/Cu FGM, although micro-cracks occurred in the surface of the pure W layer, the integrity of the bulk material remained unaffected after 50 quenching cycles. This result is in agreement with the numerical analysis. According to our FEM analysis, the thermal stress in the W surface of six-layer W/Cu FGM are much lower than that of W–Cu laminated materials, especially in the place of 2–3 mm to the surface of W layer (for W–Cu laminated materials, this place is just at the interface between W and Cu). This demonstrated that the grading at the interface between W and Cu was very effective for the reduction of thermal stress.

3.4. High heat flux test

A Nd:YAG laser beam with a 10-ms pulse length, wave length of 1.06 μm and frequency of 5 Hz, was used for high heat flux testing. The laser beam diameter is about 2 mm. The distribution of the beam power densities showed an approximate Gaussian profile. Argon was used to protect the samples from oxidation during the test. The bottom

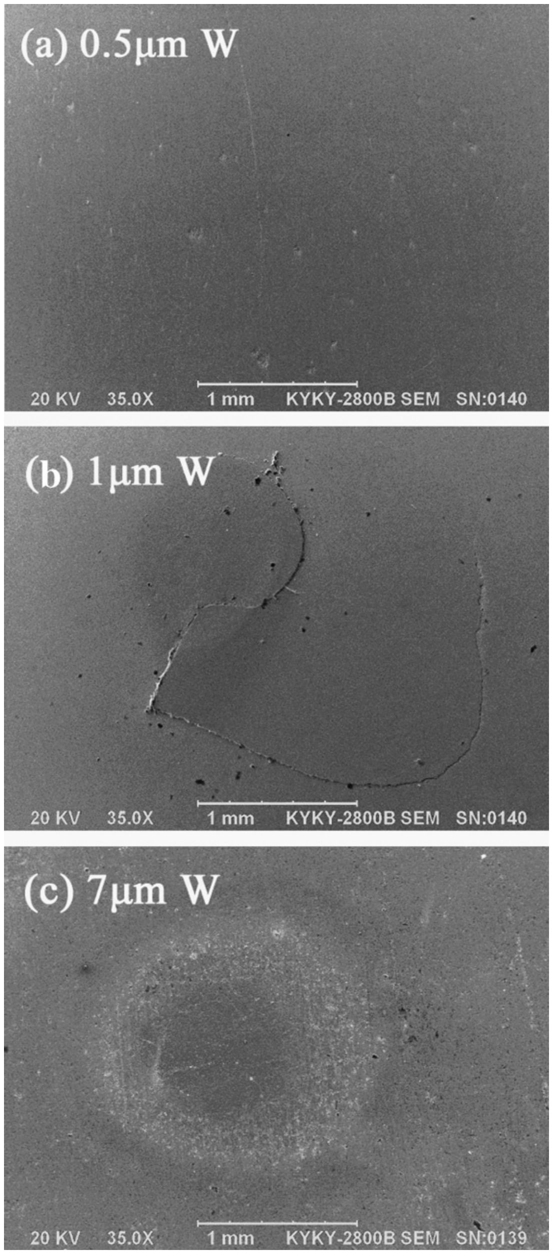

Fig. 3. SEM micrograph of tungsten surface after high heat flux testing (198 MW/m^2, 600 cycles): (a) W with 0.5 μm grain size, (b) W with 1 μm grain size and (c) W with 7 μm grain size.

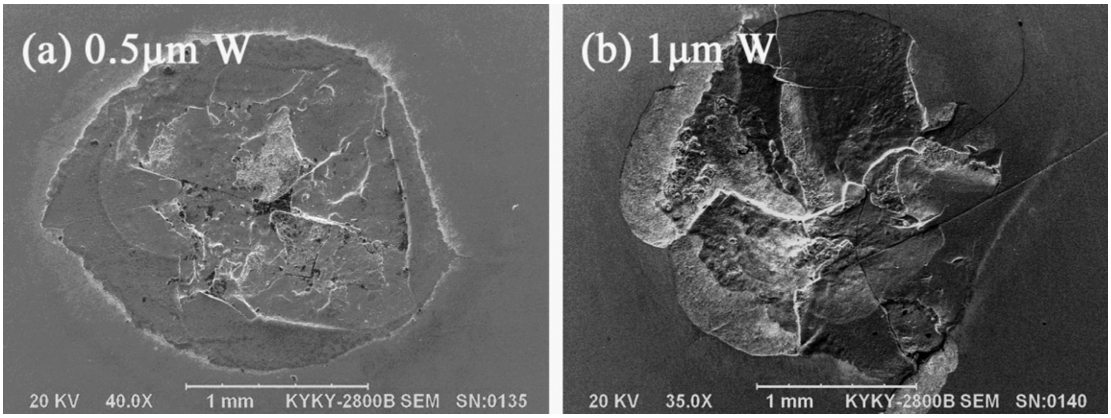

Fig. 4. SEM micrograph of tungsten surface after high heat flux testing (220 MW/m^2, 300 cycles). (a) W with 0.5 μm grain size (b) W with 1 μm grain size.

of the samples was immersed into flowing water. Although the laser beam was not a perfect method for high heat flux testing, it was useful for comparison of thermal resistance between samples of the same materials.

Fig. 3 shows the morphology of tungsten with different grain size after 600 cycles of irradiation with a laser heat flux of 198 MW/m^2. No change occurred in the surface of tungsten with sub-micron grain size. In the tungsten specimens with grain size larger than 1 μm, an obvious cratering occurred, and the larger the grain size of tungsten, the larger the crater.

The details of the W surface morphologies after 300 cycles of irradiation with a higher heat flux of 220 MW/m^2 are presented in Fig. 4. The crater morphologies under the laser spot for all pure tungsten samples revealed much evaporation during the testing. But for the W/Cu FGM sample, there was no change in the surface of tungsten layer. Only when the heat flux increased to 264 MW/m^2, obvious crater appeared in the surface of W/Cu FGM after 50 cycles of irradiation. This demonstrated that W/Cu FGM has higher thermal resistance than pure tungsten. This may be due to the higher thermal conductivity of W/Cu FGM as compared with pure tungsten, which conducts heat out of the sample more effectively.

4. Conclusions

Both fine grain sized tungsten and W/Cu FGM have been fabricated by resistance sintering under ultra-high pressure. The densities of the samples are higher than 95%.

When the grain size of tungsten decreases, its micro-hardness and bend strength will increase significantly.

Thermal shock testing by water quenching demonstrated that the grading at the interface between W and Cu was very effective for the reduction of thermal stress.

The high heat flux testing with a laser beam showed that tungsten with sub-micron grain size had higher thermal resistance than that of tungsten with grain size larger than 1 μm. W/Cu FGM endured higher heat fluxes than pure tungsten.

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