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Behaviors of full compositional W/Cu functionally gradient materials exposed to the edge plasma of HT-7 tokamak

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ABSTRACT

To investigate the behaviors of graded structure materials under plasma loading, six-layered W/Cu functionally gradient materials (FGMs) with full compositional distributions (from 0% to 100%) were successfully fabricated by resistance sintering under ultra-high pressure (RSUHP) method and were exposed to the edge plasma of the HT-7 tokamak. After about 210 shots plasma loading with an estimated power density in the range of 2–7 MW/m^2, there is no detaching found at the graded interface corners where the thermal stress concentration is expected and the fatigue failures often occur initially, however, the brittle W layer develops the macroscopic cracks which can extend deeply into the interface and results in the interface failure or even the exfoliated W layer. To avoid these destructions for W/Cu FGMs during wall application, it is necessary to ameliorate the W layer by optimizing the initial powders and sintering parameters.

1. Introduction

Plasma facing components in fusion devices consist of plasma facing materials and heat sink materials, with special requirements for different material properties [1,2]. Currently, tungsten (W) is a most likely plasma facing material, because of its high energy threshold for physical sputtering, high melting point and low tritium retention. It has been widely used in existing tokamaks (EAST, JET, ASDEX, etc.) and is foreseen as the full plasma facing material in the activated phase of ITER [3–6]. Furthermore, it is also the most suitable candidate for the first wall material in DEMO and future fusion reactors [6–8]. Meanwhile, copper (Cu) has been proposed as the heat sink material behind plasma facing material due to its excellent thermo-mechanical properties, especially the high thermal conductivity [9]. Nevertheless, because of the well-known large difference of coefficient of thermal expansion (CTE) between W and Cu, the joining of these two dissimilar materials causes the high thermal stress concentration at the interface when exposed to the high heat loads. The stress concentration may lead to the interface cracking and other forms of failure, reducing the lifetime of the components.

To mitigate the damage caused by the thermal stress, the macro-brush flat type and lamellar mono-block structures have been proposed from the engineering point of view [10]. The advantage of the brush and lamellar structure is that the single elements are free to expand under the heat flux, thus reducing the thermal stress. Another solution concept to this problem is to deal with a W/Cu functionally graded layers between W and Cu, which can provide a smooth transition of properties to alleviate the thermal mismatch [11]. Producing high quality W/Cu FGMs is always a technological challenge. Due to the large melting point difference between these two metals, there is no overlap of the sintering temperature ranges, which leads to difficulties to sinter the W/Cu FGMs by traditional methods. Using the sintering-infiltration technology, W/Cu FGM composites were successfully fabricated, whose heat flux resistance can reach up to 15 MW/m^2 [12]. However, it does not fabricate the W/Cu FGMs with compositional distributions from 0% to 100%, and still needs another method to join with W and Cu. As an alternative method, resistance sintering under ultra-high pressure (RSUHP) which can overcome this drawback utilizes the special consolidation mechanism to sinter the full compositional W/Cu FGMs [13]. Moreover, using this method the crystal grain size, especially the W layer can be well refined. The detailed fabrication processes and the simulation tests of these W/Cu FGMs are reported in the previous work [14,15]. However, the behaviors of these kinds of graded structure materials under plasma environment related to tokamak devices are unclear. Therefore, the studies on their performances under plasma loading in existing tokamak are great interest and essential.

In this work, to investigate the performance under actual plasma loading, six-layered W/Cu FGMs with full compositional distributions were successfully fabricated by RSUHP method and were

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exposed to the edge plasma in the scrape off layer (SOL) of the HT-7 tokamak.

2. Experiment

2.1. Material processing by RSUHP method

For the pure W layer and pure Cu layer of FGMs, small W powders (average size of 2.0 μm and purity >99.9%) and large Cu powders (average size <74.0 μm and purity >99.9%) were used, respectively, without any pre-treatment. While for the gradient layers, large W powders (average size of 10.0 μm and purity >99.9%) and large Cu powders (average size <74.0 μm and purity >99.9%) were mixed in an agate mortar. The compositions (volume fractions) of each layer are designed as follows: 100%W, 80%W–20%Cu, 60%W–40%Cu, 40%W–60%Cu, 20%W–80%Cu, and 100%Cu. The detailed fabricated processes can be found in the previous work [13]. The sintered parameters were: ultra-high pressure of 10 GPa, electron current of 950 A and sintering time of 60 s. The thickness for surface W layer, each graded layer and bottom Cu layer was pre-designed as 2, 1 and 6 mm, respectively.

2.2. Plasma loading test in the SOL of the HT-7 tokamak

The plasma loading experiment setup is schematically shown in Fig. 1. HT-7 tokamak is a limiter tokamak with circular plasma of a minor radius of 270 mm and a major radius of 1220 mm. The plasma is limited by three limiters. In this experiment, it had been operated with plasma current of 150 kA, average electron density of 1.8×10^{19} m^{-3}, average discharge duration of 1 s, toroidal magnetic field of 1.85 T and low hybrid current drive heating power of 300–500 kW, etc. The dimension size of W/Cu FGM specimens is 10 mm × 10 mm × 12 mm. The specimens were mechanically fixed by a screw on a stainless steel supporter and were inserted horizontally into the SOL by means of a magnetic transporter. The distance between the specimens surface and the last closed flux surface was fixed as 10 mm. The heat load deposited on the specimen surface could be estimated in the range of 2–7 MW/m^2 [16]. In particular, the specimens were not actively cooled during exposure. The specimen surface facing the edge plasma experienced 210 plasma discharges, while the edge sides were protected by a circle strain steel diaphragm during exposure. Surface component analysis and metallographic observation were performed on the surface and cross-section of the W/Cu FGMs in the sintered state and after exposure, respectively.

3. Results and discussion

3.1. Characterization of the W/Cu FGM

The relative density of the whole W/Cu FGM can reach up to 98.5%, while for the top W layer the relative density is only 95.7%. Fig. 2 is the image of the cross-section of the overall six-layered W/Cu FGM. The line scanning of the component distribution shows a graded distribution of the W and Cu. One can see the clear interfaces and the thickness of each layer is approximately 1 mm, in consistent with the pre-designed structure. Also there have well combines between gradient layers. Fig. 3 shows the backscattering images of the graded layers, in which the white phase is W while the black phase is Cu. The Cu is homogenously distributed in W matrix in the W-dominated layers, while the W is homogenously distributed in Cu phase in the Cu-dominated layers. No obvious agglomeration, segregation and migration occur during materials processing. Fig. 4 shows the component distributions (volume fraction) roughly measured by energy dispersive spectrometer (EDS). The volume fraction of Cu in each graded layer is in good agreement with that of the pre-designed one. However, it also should be noted that the measured values are slightly higher than that of the pre-designed ones, which implies the trend of Cu migration from bottom to surface. In general, the Cu migration is generated due to the high plastic flowing of Cu material under external ultra-high pressure, but it shows not significant because of the short sintering time. In addition, the grain size shows the same as the initial powders, illustrating that the grain growth is suppressed during sintering process by RSUHP method.

3.2. Surface composition analysis

The surface composition was analyzed by X-Ray fluorescence (XRF) and X-Ray diffraction (XRD) before and after exposure. Table 1 lists the surface elements measured by XRF. A small quantity of Cr, Mn, Mo, Ge and Rh (<0.07%) were detected besides the W (99.92%) and Fe (0.08%) which existed in the initial surface. Besides the strong W peaks, no extra peak was measured by XRD. The other elements are originated from the stainless steel liner, Mo limiter and first wall of the HT-7 tokamak and were introduced by the

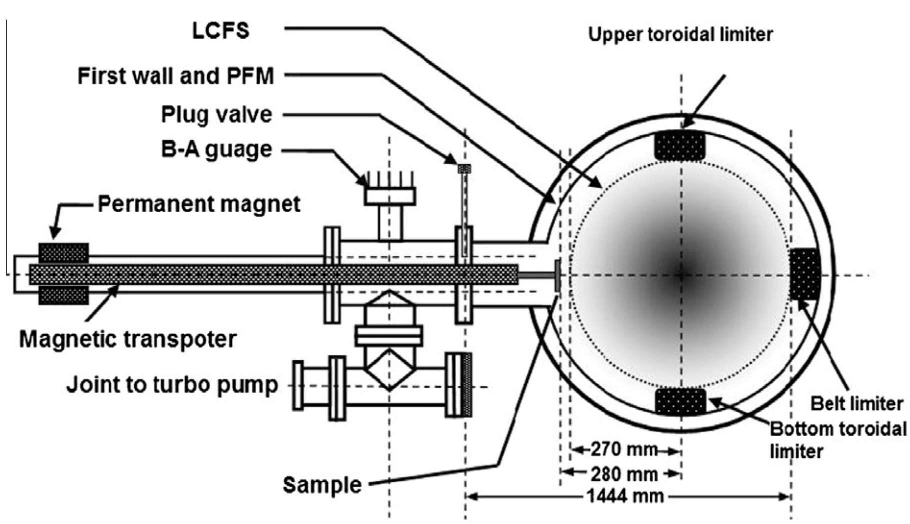

Fig. 1. Schematic view of the plasma loading experiment setup, i.e. cross-section view of the HT-7 tokamak as well as the magnetic transporter.

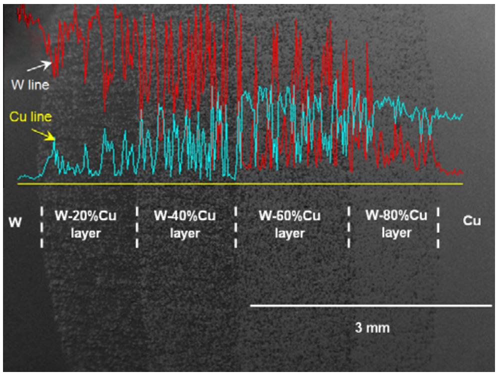

Fig. 2. The image of the overall six-layered W/Cu FGM.

deposition processes. Equally, the XRF and XRD results of W/Cu FGM surface show little contamination and no excessive compound formation during plasma exposure.

3.3. Changes of surface and cross-section morphology

After plasma exposure, post-mortem inspections were carried out by scanning electron microscopy (SEM). The surface of the W/Cu FGM after exposure shows nearly the same metallic luster as a fresh surface, approving the above analysis of the surface composition. There is no detaching found at the interface corners where the stress concentration is expected to occur, illustrating the good thermal resistance of W/Cu FGM. However, large macro cracks formed on its surface, but completely absent on a fresh surface before plasma exposure. The typical macro cracks morphology at surface is shown in Fig. 5a. The macro cracks can be visible seen, whose width can reach up to 20 μm, as shown in Fig. 5b. It also shows that the cracks were created at grain boundaries and propagated through the grain boundaries. Another remarkable phenomenon is that the macro cracks often exhibit hackle traces through both surface and thickness, as shown in Fig. 5c. These would result in the exfoliation of W particles which is shown in Fig. 5d, and afterward the formation of W dust which is hazardous to the burning plasma. Moreover, one can see many scattered W dust particles re-depositing on the exposed surface. Unfortunately, the formation mechanism is still unclear currently and needs further efforts.

Fig. 6 shows the cracks morphology through cross-section. In Fig. 6a one can see the macro cracks running over the whole W layer. In addition, the macro crack tends to propagate through the horizontal direction when it extended deeply into the interface,

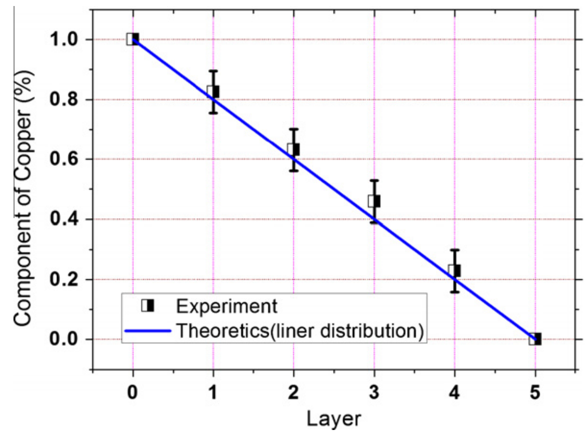

Fig. 4. The component distributions (volume fraction) of Cu in W/Cu FGM roughly measured by EDS.

Table 1
Surface component analysis on W/Cu FGM before and after exposure using XRF.

Metallic elements	Before (%)	After (%)
W	99.92	99.78
Fe	0.079	0.08
Mo	–	<0.06
Cr	–	<0.07
Mn	–	<0.06
Ge	–	<0.06
Rh	–	<0.06

as shown in Fig. 6b. Obviously, the development of crack causes local deterioration of thermal conductivity and thus the overheating of the local pre-damaged part results in the propagation of preformed cracks through grain boundary to alleviate the thermal stress. However, the presence of highly plastic copper within the gradient layers prevents cracks propagation into the graded layers. As a result, the crack spreads through the horizontal direction, especially through the interface, causing the interface failure and afterward the exfoliated W layer.

The formation of such macro cracks is not surprising, because W material develops large macro cracks under slow transients (few seconds) high heat loads, due to its low temperature brittleness properties. Altogether the W/Cu FGM specimens were not actively cooled, the initial temperatures before each plasma discharge were around 150 °C, below the ductile to brittle transition temperature (DBTT, ~400 °C). Under these conditions, serious cracking was always obtained on a W brush limiter exposed in the TEXTER toka-

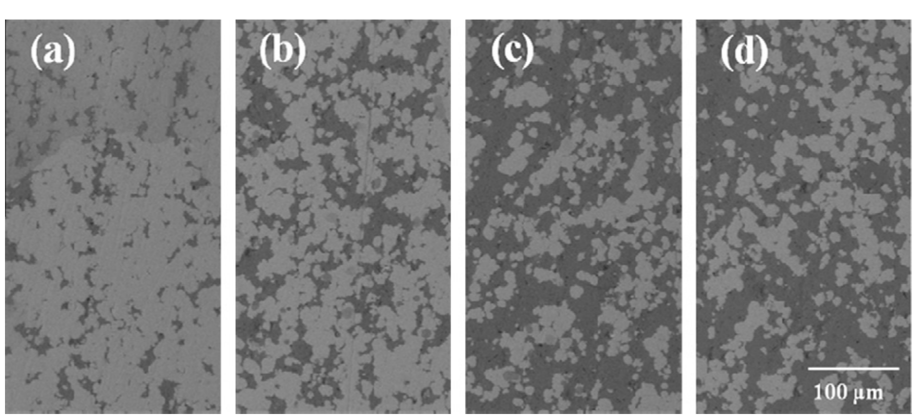

Fig. 3. The backscattering images of the (a) W-20%Cu layer; (b) W-40%Cu layer; (c) W-60%Cu layer; and (d) W-80%Cu layer.

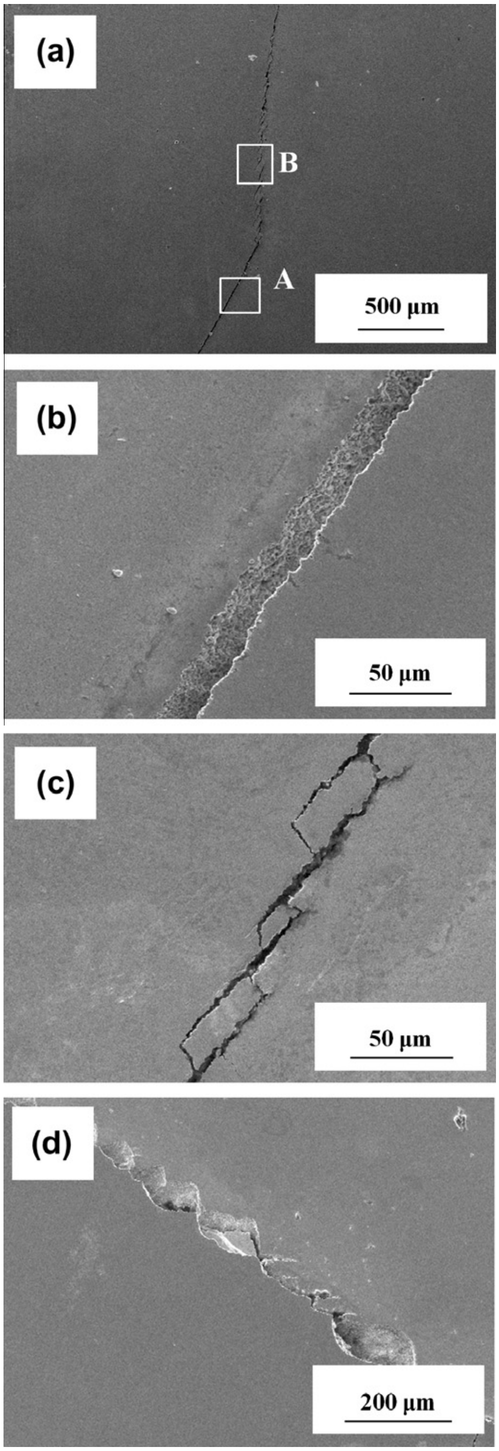

Fig. 5. The macro crack morphology at surface: (a) general morphology; (b) magnification of area A showing the crack width and micro morphology; (c) magnification of area B showing the typical crack trace; and (d) exfoliated W particles leaving the typical crack trace.

mak [17]. These macro cracks may be avoided if the base temperature of W exceeds its DBTT, which is suggested to be operated in the future devices with W armors. On the other hand, in spite of the ultra-fine grained crystal for the W layer can be obtained by using RSUHP method, its brittleness behavior shows no significant amelioration, which may be related to its low density and another unknown factors. Thus the amelioration of the W layer by optimization of the initial powders and sintering parameters is exigent for future work.

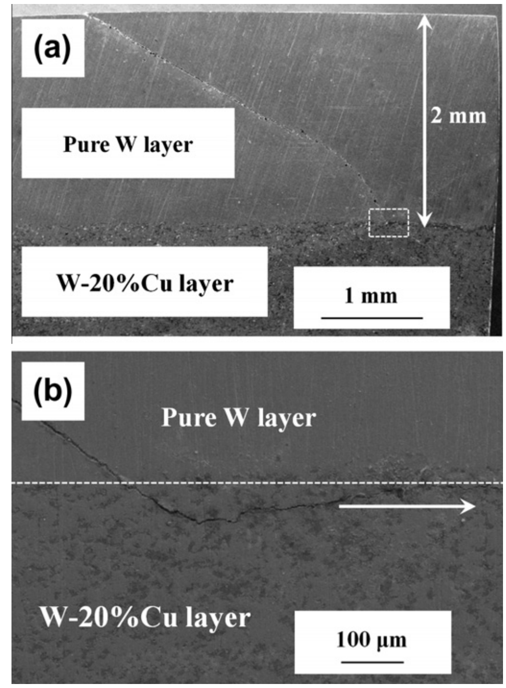

Fig. 6. The macro crack morphology through cross-section: (a) crack running over the whole W layer; and (b) crack propagation through interface.

4. Conclusion

Six-layered W/Cu FGMs with full compositional distributions were successfully fabricated using the RSUHP method and were exposed to the edge plasma in the SOL of the HT-7 tokamak. After about 210 shots plasma loading with an estimated power density in the range of 2–7 MW/m^2, there is no visible impurities deposition and compound formation at the surface and no detaching found at the graded interface corner where the stress concentration is expected. However, the brittle W layer develops macroscopic cracks. These macro cracks can extend deeply into the interface and results in the interface failure or even exfoliated W layer. Hence, the performance of the surface W layer is a critical issue which influences the behaviors of whole W/Cu FGM, and should be of special concern during materials processing. To avoid these destructions, the amelioration of the W layer by optimizing the initial powders and sintering parameters is exigent.

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