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Manufacturing and testing W/Cu functionally graded material mock-ups for plasma facing components

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Abstract

The W/Cu functionally graded material (FGM) mock-ups were manufactured by resistance sintering under ultrahigh pressure or three times hot pressing. The bonding strength of W/Cu FGM was determined by tensile and shearing tests. A thermodiffusion experiment was used for testing thermal conductivity of the region containing W, the first and second W–Cu alloy layers. High heat flux and thermal fatigue tests have been carried out using electron beam or laser. The results are that the specimens with higher density in the W layer have better performances in high heat flux and thermal fatigue tests. Using the above sintering techniques, W/Cu FGM mock-ups for plasma facing components have been successfully manufactured at less cost.

1. Introduction

According to the required material characteristics for plasma-facing components in the International Thermonuclear Experimental Reactor (ITER) or other fusion reactors, W or W alloys are considered for divertor structural and armour application because of many favorable properties such as high melting point, high thermal conductivity, longer lifetime, etc. [1–3]. In order to provide high heat removal capability W or W alloys joined to a Cu heat sink are likely to be the best choice [4–6].

Tungsten layers of more than 5 mm thickness, as required for the ITER, are now available. The thermophysical properties of CVD-W are typically at least as good as pure W, whereas due to the texture and residual porosity in plasma-sprayed (PS)-W, it has only ~20% of the thermal conductivity of pure W [4]. When the coating is performed in a low-pressure inert argon atmosphere ('vacuum'-plasma-spraying), the VPS-W coatings achieve ~60% of the thermal conductivity measured for pure tungsten [4].

One of the disadvantages of the CVD technique is the high production cost. From the economic point of view, a tungsten plasma spray method at low pressure is attractive. A 5 mm thick pure tungsten layer with a 2.5 mm thick W–Cu functionally graded material (FGM) layer was successfully produced on a copper heat sink with the low pressure plasma spray method [7–9].

Joining of W Macrobrush, W Monoblock, W lamella or W Rod to copper heat sinks has been

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intensively studied for the divertor in ITER [10,11]. Hot isostatic pressing (HIP) bonding technology of W (tungsten) and Cu-alloys have been developed to fabricate plasma facing components for the fusion reactor [12].

Due to the differences in the coefficient of thermal expansion and Young's modulus, the joining of W and Cu results in high residual and thermal stresses at their interface when a W/Cu mock-up is exposed to high heat loads. These stresses may lead to cracking, delamination and detachment reducing lifetime of the components. The thermal stresses can be reduced by adding a graded interlayer in which the composition has been designed optimally using finite element analysis [13–15].

Copper is ductile so that this paper considered its plastic behavior when analyzed W/Cu FGM by the finite element method. The W/Cu FGM mock-ups were manufactured by resistance sintering under ultrahigh pressure or three times hot pressing.

2. Experiment

Purity of the W tile being used in hot pressing was 99.96% and density was 19.1 g/cm^3, impurity concentrations were (%): Al < 0.002, Ca < 0.005, Fe < 0.005, Mg < 0.003, Mo < 0.010, Ni < 0.003, Si < 0.005, C < 0.008, N < 0.003 and O < 0.005.

A W powder produced by Zhuzou Hardmetal Co. with an average particle size of 1–3 μm and purity greater than 99.9%, and an electrolytic Cu powder with a particle size of 74 μm and purity greater than 99% were used.

A mock-up was formed in three sections with different materials. At the top, a 5 mm thick W armor faces the plasma in order to insure longer lifetime. Joined to the W armor, a 5 mm thick W/Cu FGM as an interlayer relaxes thermal stresses under operating conditions. At the bottom, a 20 mm thick Cu heat sink dissipates heat by means of water flowing through a 15 mm diameter channel.

For simplicity, a bilinear kinematic hardening law that obeys the von Mises yield criteria was used for describing plasticity behavior of the W/Cu FGM. The optimal value of the compositional exponent p, layer number n and thickness h are, respectively, 1.5, 5 and 5 mm in the W/Cu FGM determined using finite element methods. Because Cu is less in layer 1, 6 vol.% Ni was added instead of W to carry out activated sintering.

The W/Cu FGM mock-ups were manufactured by three times hot pressing because the sintering temperatures of each layer are different. W/Cu FGM mock-ups were also manufactured by a resistance sintering under ultrahigh pressure.

Tensile tests were made at room temperature in the symmetrical composition-graded direction of the multi-layer bulk FGMs 10×10 mm in section. Total length of the specimens was 55 mm, with 20 mm Cu + 5 mm W/Cu FGM + 5 mm W + 5 mm W/Cu FGM + 20 mm Cu.

Because the tensile test can only measure strength between weakest two layers, a shearing test was used for measuring inter-laminar shear strength between every pair of layers.

Thermal conductivity (λ) of the specimen was calculated by thermodiffusion coefficients (α) which were measured in the China Aerospace Science and Technology Corporation. The formula is $\lambda = \alpha \cdot C_P \cdot \rho$. Specific heat ($C_P$) was calculated according to the data in some handbooks and the rule of mixture. Density (ρ) was measured by Archimedes principle. Three layers specimen was about 2.5 mm in thickness, with 0.5 mm W layer, 1mm first layer W/Cu and 1 mm second layer W/Cu in the W/Cu FGM.

High heat flux tests were carried out using an electron beam in the Institute of Plasma Physics, Chinese Academy of Sciences with a vacuum of 2.1×10^{-2} Pa. The diameter of the electron beam was 5 mm. The cyclic scan frequency was 200 Hz, and the irradiated area was 25×30 mm. The steady-state heat flux was 4 MW/m^2 and steady-state irradiation time was 60 s.

The flow rate, pressure and inlet temperature of the cooling water were 10 m/s, 0.4 MPa and 25 °C, respectively.

Thermal fatigue tests were carried out using a laser beam in the China Daheng Laser Engineering Co with Nd/YAG laser, a laser wavelength of 1.06 μm, average laser power of 120 W, pulse energy of 40 J, a pulse width of 10 ms, and a frequency of 5 Hz. The bottom of specimens was in contact with water.

3. Results and discussion

W tiles are joined to the W/Cu FGM and Cu heat sink to form a flat-type configuration by three times hot pressing as shown in Fig. 1.

Using techniques of the resistance sintering under ultrahigh pressure, a W/Cu FGM mockup of a divertor target has been manufactured. Fig. 2 shows a view schematic and photos of the completed

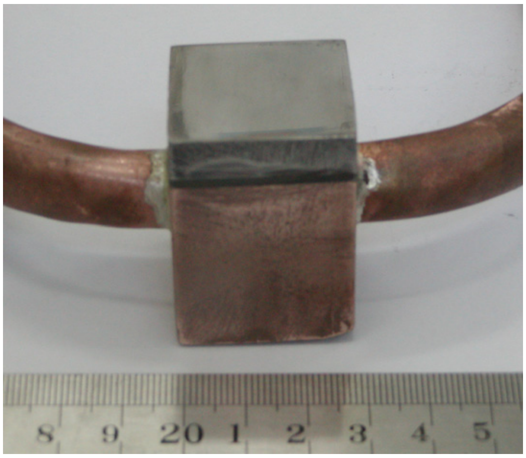

Fig. 1. A W/Cu FGM mock-up made by hot pressing for cyclic heat load experiment by electron beam.

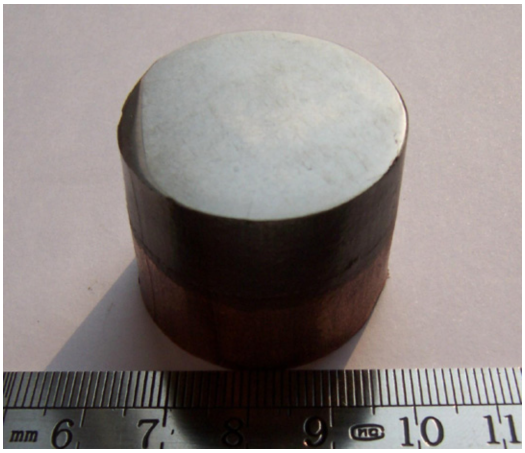

Fig. 2. A W/Cu FGM mock-up made by resistance sintering under ultrahigh pressure.

W/Cu FGM. In this W/Cu FGM, an interlayer of W/Cu FGM with a thickness of 5 mm has been applied to relieve thermal stresses caused by the difference in thermal expansion between 5 mm W and 20 mm Cu.

The W/Cu FGM interlayer thickness was optimized for the W tile by an elastoplastic thermal stress analysis under the assumed steady-state heat flux of 5 MW/m^2 on the plasma side of the W tile with heat transfer by water flowing through a 15 mm diameter Cu pipe at 20 °C, 3 MPa and 10 m/s.

Tensile strengths and inter-laminar shear strengths of W/Cu FGM prepared by hot pressing are shown in Table 1. The fracture occurred always between the third and fourth layers.

Inter-laminar shear strengths of W–1%TiC/Cu FGM prepared by resistance sintering under ultrahigh pressure are 36.32 MPa between the fifth layer and Cu, and 23.01 MPa between W and layer 1 with section of 10×10 mm.

Table 1
Tensile strength and inter-laminar shear strength of W/Cu FGM produced by hot pressing

Specimen	Section (mm × mm)	Tensile load (kN)	Tensile strength (MPa)	Fracture position
1	9.66×9.92	2.562	26.74	Between third and fourth layers
2	10.62×9.92	2.558	24.28	Between third and fourth layers
3	9.52×9.88	2.665	28.33	Between third and fourth layers
4	9.86×10.68	3.066	29.12	Between third and fourth layers
		Shearing load (kN)	Shearing strength (MPa)	
5	9.74×9.92	22.33	231.11	Between third and fourth layers
6	9.70×9.90	10.05	104.65	Between third and fourth layers
7	10.46×9.96	4.870	46.75	Between third and fourth layers
8	10.28×11.06	7.034	61.87	Between fifth and Cu layers

The first specimen was 92.59% W, 7.46% Cu which is 10 mm diameter × 2.6 mm long with a measured density of 17.77 kg/m^3. The measured thermodiffusion coefficient was 4.70×10^{-5} m^2/s and calculated specific heat was 160.48 J/kg K. The calculated thermal conductivity was 134.03 W/m K. The second specimen was 90.59% W, 9.41% Cu which is 10 mm diameter × 2.6 mm with a measured density of 17.41 kg/m^3. The measured thermodiffusion coefficient was 4.79×10^{-5} m^2/s and calculated specific heat was 165.21 J/kg K. The calculated thermal conductivity was 137.78 W/m K.

There was no fracture between W and W/Cu FGM, no fracture between every two W/Cu FGM layers after high heat flux tests. Results of thermal fatigue tests are shown in Table 2.

The higher the density of W, the longer lifetime is against thermal fatigue resistance, because porosity

Table 2
Thermal fatigue tests of W/Cu FGM

Specimen	Density of W (%)	Heat flux (MW/m^2)	Number of pulses
Hot pressing	98	20	2000
Resistance sintering under ultrahigh pressure	95	10	1000
Plasma spray	90	7	1000

in the W layer decreases significantly the thermal conductivity of W layer.

4. Conclusions

Because of the differences in the coefficient of thermal expansion and Young's modulus between W and Cu, an elastoplastic thermal stress analysis was used. The thermal stresses were lower when the compositional exponent was 1.5 in such a manner that content of Cu is less than in linear compositional exponent. An interlayer of W/Cu, with an optimal 5 mm thickness was also applied.

For ease of bonding W tiles bonded to the W/Cu FGM and Cu heat sink, a one-axis hot pressing with three heating processes has been applied to bond the three materials. Ni–Cu brazing materials have been used between the W tile and W/Cu FGM.

The 36 mm diameter × (5 mm W + 5 mm W/Cu FGM + 20 mm Cu) specimens were sintered using resistance sintering under ultrahigh pressure, which can minimize the manufacturing cost.

Using the above two sintering techniques, partial mockups for a blanket firstwall panel and divertor target have been successfully manufactured.

Acknowledgements

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