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Materials

Fabrication of W/Cu and Mo/Cu FGM as Plasma-facing Materials

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Abstract: W/Cu Functionally Graded Materials (FGM) was designed not only for reducing the thermal stress caused by the mismatch of thermal expansion coefficients, but also for combining the features of W, Mo — high plasma-erosion resistance and the advantages of Cu — high heat conductivity and ductility. Four different fabrication processes for W/Cu or Mo/Cu, including hot-pressing, Cu infiltration of sintered porosity-graded W skeleton, spark plasma sintering and plasma spraying, were investigated and compared. It was found that the hot-pressing process is difficult to keep the designed composition gradient, while the other three processes are successful in making W/Cu or Mo/Cu FGM. Meanwhile, microstructures and composition gradients are analyzed with SEM and EDAX.

Key words: FGM; plasma-facing material; W/Cu and Mo/Cu alloy

W and Mo are the leading candidates for the divertor section of the ITER due to their high plasma erosion resistance. However, to join refractory metals W or Mo to copper heat sinks meets a series of difficulties. One of these difficulties is the mismatch of thermal expansion coefficient difference and other physical properties between two joined materials, causing large thermal stress during fabrication and service and leading to cracking on the interface between W and Cu [1,2].

The idea of Functionally Graded Materials (FGM) is adopted instead of conventional coating or welding of W and Cu substrate. FGM is designed not only for reducing the thermal stress caused by mismatch of thermal expansion coefficients and other physical properties, but also for combining the feathers of W, Mo-high heat conductivity and ductility. Due to the large difference in melting point of W, Mo and Cu, and the sintering temperature of W and Mo much higher than the melting point of Cu, the main problem in development of W/Cu and Mo/Cu FGM is the selection of suitable fabrication technologies [3–5]. This paper investigated and compared four different fabrication processes for W/Cu or Mo/Cu FGM.

1 Experimental

1.1 Hot-pressing for fabrication of W/Cu FGM

The W powder produced by Zhuzou Hardmetal Co. with an average particle size of 0–3 μm and a purity greater than 99%, and the Cu powder with a particle size of −200 mesh and a purity greater than 99% were used.

According to the design of composition distribution of the FGM, the W and Cu powders were mixed with different mass ratio. Then the powders with different composition were stacked layer by layer in a steel mould to form a green compact of ϕ42 mm × 8 mm. The green compact was placed in the hot-press and sintered under Ar atmosphere with or without pressure. With pressureless sintering, the sintered product deformed seriously due to the large difference in density and thermal expansion coefficients of Cu and W. This problem can be solved with hot-pressing.

To ensure the highest density of the product, hot pressing had to be carried out at a temperature higher than the melting point of Cu. It is shown that liquid Cu would flow out of the sample and lost when the mass fraction $w_{Cu} > 50\%$, while Cu would not flow out as $w_{Cu} < 50\%$. The FGM specimens of ϕ42 mm×4.84 mm with a relative density of 94.6% were produced with the flow scheme shown in **figure 1**.

Figure 2 show the SEM micrographs of a hot-pressed specimen. The specimen was hot-pressed at a high temperature for quite long time. Remarkable liquid Cu migration occurred and boundaries between layers disappeared. The graded composition differences between layers reduced and deviated from the designed composition gradation.

The specimen was heated for 5 min at 600℃ in air, and then quenched in cold water. No macrocrack appeared after 50 cycles.

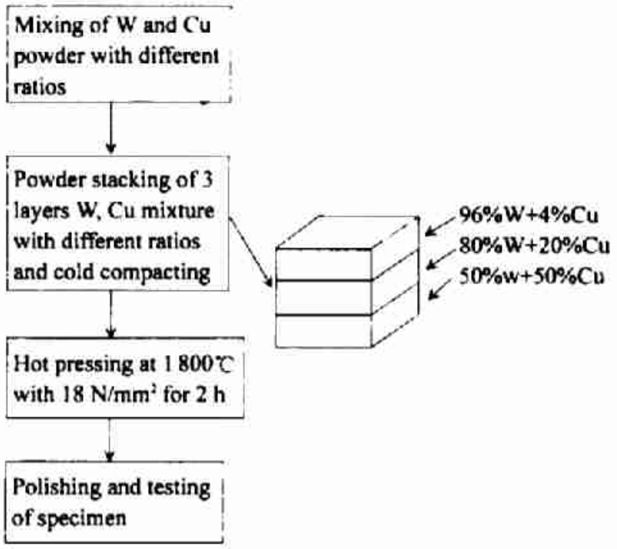

Figure 1 Flow scheme for hot-pressing of W/Cu FGM.

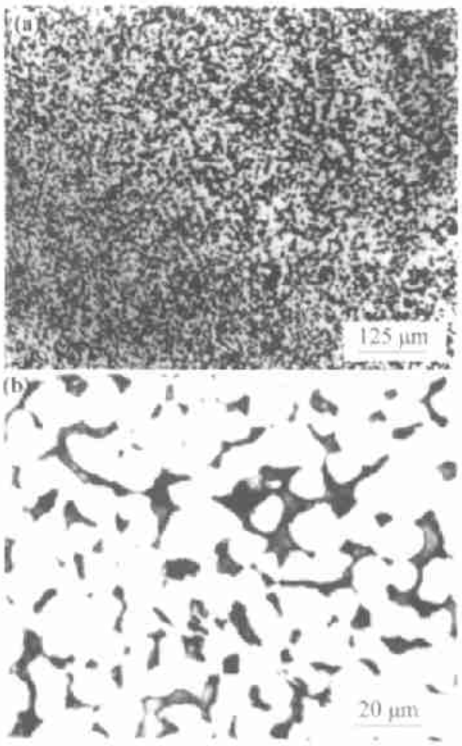

Figure 2 SEM of HP-W/Cu FGM for 2 h. (a) Three layers, and (b) middle layer.

1.2 Spark plasma sintering for fabrication of Mo/Cu FGM

The Spark Plasma Sintering (SPS) process is a new material processing technology recently developed by Sumitomo Coal Mining Co. Ltd., Japan. In addition to heat and external pressure applied in the specimen during conventional hot-pressing, a direct-current pulse voltage from a special electric source was overlapped and spark plasma charge occurred between particles producing local high temperature and causing melt and evaporation of particle surfaces and particle welding. A series of effects due to generation of spark plasma were produced: broken of oxide skins on the particles and surface activation, high density energy supply, efficient heating and plastic deformation promotion, high-speed diffusion and mutual transfer, dispersed movement of discharge points, quick cooling of intergranular bonding *etc.*. All these effects lead to low temperature, short time and uniform sintering, sintering of hard sintered materials, and bonding of dissimilar materials. It is most suitable for sintering FGM, especially when a graded graphite die is used to create a graded temperature field during SPS process.

The Mo, Cu and Ni powders with −200 mesh and 99.9% purity were used, and the 4-layered green compacts of ϕ10 mm×10 mm with each layer of 2.5 mm in thickness were made by powder stacking process. The composition of each layer is 99%Mo + 1%Ni + 29.5% Cu, 69.5%Mo + 1% Ni + 29.5%Cu, 49.5%Mo + 1%Ni +49.5%Cu, and 29.5%Mo + 1%Ni + 69.5%Cu in mass fraction, respectively.

The SPS process was carried out under 30 MPa for 5 min at 850℃. **Figure 3** shows that the interfaces between the layers are clear, indicating no evident migration of Cu occurred due to absence of liquid copper and short time sintering.

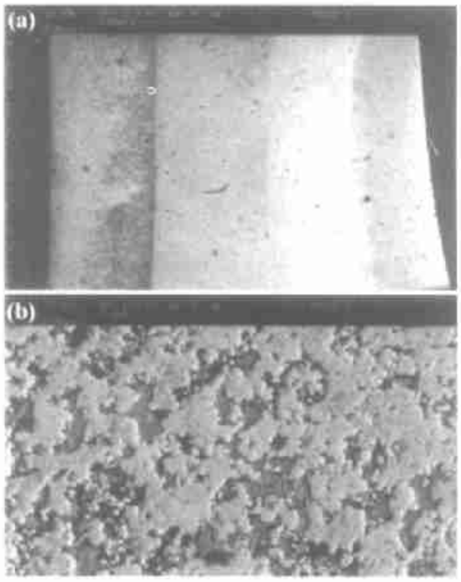

Figure 3 SEM micrographs of SPS Mo/Cu FGM. (a) Three layers, and (b) middle layer.

1.3 Cu Infiltration of porosity-graded W skeleton — welding process for fabrication of W/Cu FGM

The W powders with particle sizes of 3, 7 and 15 μm respectively and a purity of 99.9% and the Cu powder of −200 mesh and 99% purity were used. These W powders with different particle sizes were mixed separately with a pore-making agent in an agate mill. A green compact of ϕ40 mm×3 mm was pressed in a steel die, then put in a graphite crucible embeded with Al_2O_3 powder and sintered in H_2 atmosphere at 1 300℃ for 1 h. A porosity-graded W skeleton was formed. The calculated mass of Cu powder was then placed on the top of the W skeleton sintered at 1 300℃ for 30 min, and the melted Cu flowed into the pores of the W skeleton and the residual Cu kept on the surface as the 100%Cu layer. Three variants for making porous W skeletons were compared in **table 1**.

It is noticed that the graded distribution of composition are formed in specimens A, B and C. After infiltration with liquid Cu, the Cu grains in specimen A are much coarser than those in specimens B and C, as the coarser pores formed after sintering of the W skeleton. The stepwise gradation of Cu distribution is shown in specimen B. While the best, near continuous distribution of Cu is formed in specimen C. **Figure 4** shows the SEM micrographs of specimens A, B and C.

Table 1 Three variants of making porous graded W skeleton.

Specimen A

Layer No.	W powder (5 μm) / g	Pore-making agent / g	Pore volume / %
1	18	0.06	5
2	16	0.39	30
3	14	0.80	70

Specimen B

Layer No.	W powder (3 μm) / g	Pore-making agent / g	Pore volume / %
1	18	0.06	5
2	16	0.39	30
3	14	0.80	70

Specimen C

Layer No.	Size of W powder / μm	Mass of W powder / g	Pore-making agent / g	Pore volume / %
1	3	18	0.06	5
2	7	16	0.39	30
3	15	14	0.39	70

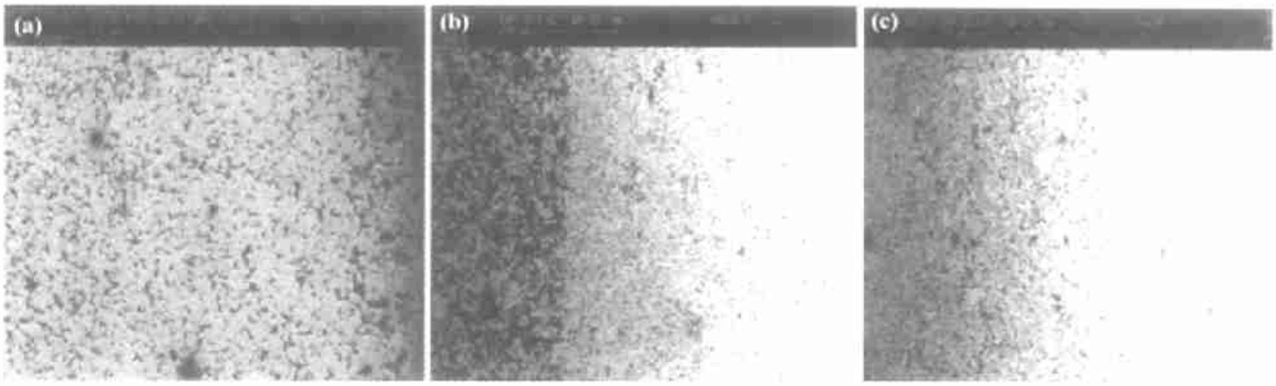

Figure 4 SEM micrographs of the specimens A (a), B (b) and C (c).

A W was welded on the other surface of the graded specimen and a W/Cu FGM with 5 layers from 100% Cu on the top surface to 100% W on the bottom surface was obtained.

The linear expansion coefficient and the flexural strength of specimen A, B and C are shown in **tables 2 and 3**, respectively. The high linear expansion coefficient is attributed to the network distribution of Cu in the specimens. The bonding strength between W layer and the transition layers are 12.41 MPa. The specimen was heated in a $MoSi_2$ furnace to 500 ℃, kept for 5 min after 30 cycles.

The W powder with a particle size of 30-76 μm and the Cu powder with a particle size of 45-76 μm were

Table 2 Thermal expansion coefficient *α* of the specimens.

Specimen	A	B	C
α_l / 10^{-6}m·℃$^{-1}$	15.96	14.70	13.13

Table 3 Flexural strength of W/Cu FGM specimens.

Specimen	H / mm	B / mm	L / mm	P / N	σ_w / MPa
A1	2.56	4.64	30	285	421
A2	2.70	4.68	30	311	410
B1	2.72	4.52	30	436	586
B2	2.76	4.70	30	571	717
C1	2.39	3.94	30	296	591
C2	2.72	4.50	30	390	527

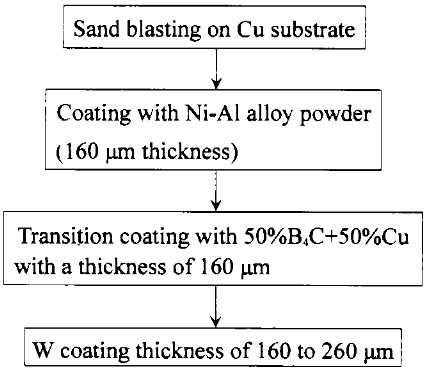

Figure 5 Fabrication route of W/Cu coating FGM.

used for plasma spraying. The fabrication route is shown in **figure 5.**

2 Discussion

The above mentioned work showed that each variants of fabrication process had its own features, the features of each process are summarized as follows.

For hot-pressing,

(1) Only relatively narrow composition spectrum is possible (w_{Cu}=4%–50%);

(2) Designed composition distribution cannot be kept due to migration of liquid Cu;

(3) The thickness of W-rich layers can be higher than 1 mm.

For sparking plasma sintering,

(1) Wide composition spectrum can be obtained (w_{Cu} =0–69.5%);

(2) The sintering temperature can be lowered greater then 200℃ and the sintering time reduced to 8% in contrast to conventional HP;

(3) FGM constituents showing large differences in melting point can be fabricated, such as Mo/Cu, W/Cu FGM;

(4) The thickness of Mo-rich layers can be higher than 1 mm.

For Cu infiltration of porosity-graded W skeleton,

(1) Whole composition spectrum from 100% Cu to 100% W can be realized;

(2) Cu network distribution is beneficial for keeping high heat conductivity;

(3) Continuously graded composition distribution is visible;

(4) The thickness of W layers can be higher than 1 mm.

For plasma spraying of W on Cu substrate,

(1) In-situ operation is suitable to large components and complex shapes;,

(2) Cost-effective;

(3) The thickness of W layers is limited, while the porosity of W layer is about 10%;

(4) Wide component spectrum from 100% Cu to 100% W can be made.

3 Conclusions

Among the four fabrication processes, the HP process is difficult to keep the designed composition gradient, while the other three processes are successful in making W/Cu and Mo/Cu FGM with different features and shows good application prospect in divertor section of fusion reactors.

Acknowledgements

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