G Model
FUSION-6780; No. of Pages 5
ARTICLE IN PRESS
Fusion Engineering and Design xxx (2013) xxx–xxx
Contents lists available at SciVerse ScienceDirect
Fusion Engineering and Design
journal homepage: www.elsevier.com/locate/fusengdes

Preparation and properties of CVD-W coated W/Cu FGM mock-ups

Youyun Lian[a,*], Xiang Liu[a], Zengyu Xu[a], Jiupeng Song[b], Yang Yu[b]

[a] *Southwestern Institute of Physics, P.O. Box 432, 610041 Chengdu, PR China*
[b] *Xiamen Honglu Tungsten and Molybdenum Industry Co. Ltd., 361021 Xiamen, PR China*

HIGHLIGHTS

- CVD-W coating was deposited at high deposition rate about 0.7 mm/h.
- CVD-W coating has high density, purity and thermal conductivity.
- Graded W/Cu composite was used as a transition layer between W coating and CuCrZr.
- CVD-W mock-ups have good thermal–mechanical properties.

ARTICLE INFO

Article history:
Received 14 September 2012
Accepted 27 February 2013
Available online xxx

Keywords:
Tungsten coating
Chemical vapor deposition
High heat load
Thermal fatigue

ABSTRACT

Tungsten was coated on a W/Cu functionally graded material (FGM) by chemical vapor deposition technique (CVD), and then the tungsten coated tile was brazed on the CuCrZr heat sink with a cooling channel. The thickness of CVD-W was 2 mm deposited by a fast rate of about 0.7 mm/h. The features of the CVD-W coating including morphology, element composition and thermal properties were characterized. A tungsten coating with high density, purity and thermal conductivity is achieved. The bonding strength between the CVD-W layer and FGM was measured using bonding tensile tests. Thermal screening and fatigue tests were performed on the CVD-W mock-ups under fusion relevant conditions using an electron beam device. Experimental results showed that the CVD-W mock-up failed by melting of Cu beneath the tungsten layer under a high heat load of 14.5 MW/m^2 and 30 s pulse duration. Thermal fatigue tests showed that the CVD-W mock-up could sustain 1000 cycles at a heat load of 11.7 MW/m^2 absorbed power density and 15 s pulse duration without visible failure.

1. Introduction

Tungsten (W) seems to be one of the most promise candidate plasma facing materials for the divertor and the first wall in fusion devices because of the low sputtering yield, high thermal conductivity, high strength at elevated temperatures and low tritium inventory [1]. Unfortunately, these advantages are coupled with serious embrittlement and difficulties in machining. A possible solution for the utilization of tungsten as plasma facing material is the coating of the heat sink or structural material with a tungsten layer [2].

Physical vapor deposition (PVD), plasma spraying (PS) and chemical vapor deposition (CVD) are the most commonly used processes to prepare tungsten coatings in industry. Tungsten deposited by CVD technique has advantage of high density and high purity, large-size products, better flexibility with shaped surfaces and better surface coverage. This technique could be one of the practicable methods for in situ repair of the damaged tungsten armor [3]. CVD-W with columnar grains can be helpful to avoid coating flaking under high heat loads. The CVD-W mock-ups have shown good heat load properties [4–7]. Thermal fatigue tests on CVD-W mock-ups with 2 mm thick W coating showed excellent performance under thermal fatigue tests of 5 MW/m^2 steady-state and 22 MW/m^2 for 10 s plus duration [4,5]. Thermal shock tests by intense electron beam show a superior resistance of CVD-W compared with sintered W [6,7]. The major concerns for application of CVD-W coating are the very low deposition rate and high fabrication costs [8]. The deposition rate is typically 0.2 mm/h [3,9], which is slow for thick coatings.

In the present work, a CVD-W coated W/Cu FGM mock-up has been developed. The CVD-W layer was prepared by Xiamen Tungsten Corporation, China. The deposition rate can be up to 0.7 mm/h. Additionally, the tail gas of the deposition experiment can be recycled and harmlessly treated. These solutions can reduce the costs of fabrication and environmental pollution. Here we focused on the thermo-mechanical performances of CVD-W prepared at high deposition rate.

* Corresponding author. Tel.: +86 82850419.
E-mail address: lianyy@swip.ac.cn (Y. Lian).

0920-3796/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.fusengdes.2013.02.155

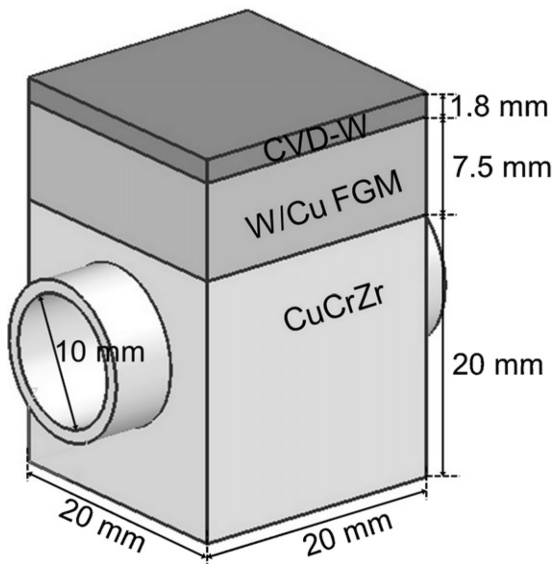

Fig. 1. Sample geometry and dimensions of CVD-W mock-up.

2. Fabrication of CVD-W mock-ups

Tungsten coating on a W/Cu functionally graded material (FGM) was prepared by CVD technique. The FGM was used as an interlayer to reduce the stresses between tungsten coating and heat sink CuCrZr alloy. The FGM with three-layered W/Cu was fabricated by a liquid phase sintering with co-reduced W–Cu composite powders [10].

Rectangular FGM tile with surface area 40 × 40 mm and thickness of 7.5 mm was machined, then polished and ultrasonically cleaned. The tungsten layer was coated on W-rich side of the cleaned tile by the chemical reaction between WF_6 and H_2 in high pressure. The purities of WF_6 and H_2 were both 99.99%. The gas mixture ratio of H_2 and WF_6 was 3:1. The mixed gas flowed into the reaction chamber at the substrate temperature about 550–650 °C. The deposition rate was in the range 0.3–1.0 mm/h and controlled by the substrate temperature, gas flow velocity and pressure during deposition process. The pressure of the reaction chamber was the key parameter for achieving high deposition rate. In the present experiment, the deposition rate of tungsten layer was 0.7 mm/h and the thickness of tungsten layer was about 2 mm.

After that, the CVD-W coated tile was machined into four parts with dimension of 20 × 20 × 9.5 mm by wire-electrode cutting method. The surface of the tungsten layer was carefully polished by mechanical way and the final thickness was about 1.8 mm. Mock-ups were made by brazing the heat sink CuCrZr alloys on the Cu-rich side of the machined tiles. Brazing experiment was performed at temperatures 950 °C in a vacuum chamber. A cooling channel in the heat sink CuCrZr alloy was drilled and a Cu cooling tube was brazed to this channel. The inner diameter of this tube was 10 mm and the outer diameter was 12 mm. Fig. 1 shows the geometry and dimensions of the mock-up.

Table 1
Characteristic properties of the CVD-W coating.

Properties	Value
Density (g/cm^3)	19.2
W content (wt.%)	99.99
Coefficient of thermal expansion (200–1000 °C, 10^{-6} K^{-1})	4.2–4.91
Hardness (RT, HVN)	430 ± 10

3. Characterization of CVD-W mock-ups

3.1. Properties of CVD-W coating

Fig. 2 shows the micrograph of cross-section of CVD-W layer. As a consequence of the growth process, the CVD-W has a columnar grain structure which is similar as reported in the literature [5,7]. The orientation of grains is perpendicular to the surface of substrate. At the beginning of deposition process, the deposition rate was slow to enhance the bonding of W coating with substrate. The grain size at the initial growth stage is smaller than in bulk as shown in Fig. 2. Microstructural observation shows that the grains in bulk generally have width of around 50 μm. It indicates that grain size of the CVD-W is dominated by deposition rate. The grain size increases with increasing the deposition rate. The average grain size of CVD-W deposited at the rate 0.2 mm/h is several μm [7], which is less than that of the CVD-W developed presently. Although the deposition rate was high, the microstructure of the tungsten layer is homogeneous and compacted. There are no voids and cracks in the bulk of tungsten layer.

Some properties of the CVD-W are summarized in Table 1. CVD technique has a number of advantages as a method for depositing high density and purity coatings. The density of the CVD-W is about 19.2 g/cm^3, which is close to the theoretical value. The tungsten content of the CVD-W is about 99.99 wt.%, which is higher than that of sintered W. The coefficient of thermal expansion of the coating was 4.2–4.91 × 10^{-6} K^{-1} (between 200 and 1000 °C), which is much less than CuCrZr alloy. The Vickers hardness of top surface tungsten coating is about 430 ± 10, which is close to the hot deformed tungsten.

Thermal conductivity is an important parameter that affects the thermo-mechanical performances of the coating under transient and steady state high heat loads. The thermal conductivity of the

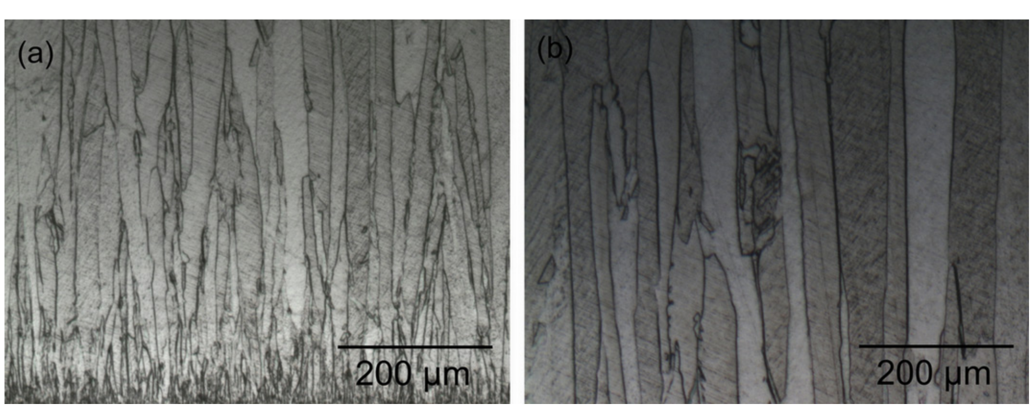

Fig. 2. Microstructure of CVD-W coating: fine grains at the bottom of the coating (a) and coarse grains in the bulk of the coating (b).

Please cite this article in press as: Y. Lian, et al., Preparation and properties of CVD-W coated W/Cu FGM mock-ups, Fusion Eng. Des. (2013), http://dx.doi.org/10.1016/j.fusengdes.2013.02.155