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ARTICLE

Thermal Performance and Microstructure of Vacuum Plasma Sprayed Tungsten Coatings under Cyclic Heat Load

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Abstract: Tungsten coatings on copper substrate were prepared by vacuum plasma spraying (VPS). NiCrAl and W75Cu25 materials were selected as intermediate layers. The experiment result of cyclic heat load of electron beam with 5 MW/M^2 (heat flux) and 2 s pulse duration indicates that NiCrAl interlayer improves the thermal conduction of the coatings and reduces their thermal and residual stress. The specimen with W75Cu25 interlayer fails with a bad thermal performance because of fabrication problems. The microstructure characterization of the VPS-W coating shows that erosion crater and fine microcracks appear on the tungsten coating after cyclic heat load tests. And erosion crater has a coarse and loose microstructure. Local plastic deformation occurs in the coating because of thermal stress. Cracks originate from debonding of molten tungsten particles at high temperature. However, the crack propagation is constrained by local plastic deformation and pores in the tungsten coating.

Key words: tungsten; vacuum plasma spraying; cyclic heat load; microstructure; intermediate layer

Both tungsten and tungsten coatings have been considered as candidate materials for plasma facing components such as limiter blocks and diverter tiles in fusion experiment devices[1-5]. They can be prepared by powder metallurgy (PM) and chemical vapor disposition (CVD) or plasma spray (PS)[6]. Plasma spraying is a prospective technology for producing plasma facing components. At present stage, tungsten coatings on light carbon materials have been successfully applied in current fusion devices such as TEXTOR and ASDEX-Upgrade [7-10]. But it is difficult to mechanically fix tungsten coated carbon on copper heat sink. So tungsten coating on copper alloy has attracted much more attention which can provide simultaneously the joining of the W amour with the heat sink to make up plasma facing material (PFM). The problems related to the manufacturing of tungsten coatings on copper substrates are low adhesion and the high residual stresses following the deposition process due to the difference in the expansion coefficient, which is smaller for tungsten than for copper [11]. An intermediate bonding layer with an intermediate thermal expansion coefficient and high compliance was selected to achieve a good thermal shock resistance of the coating, i.e., to obtain high adhesion to the copper and improve thermal conduction. It is a key issue to select an intermediate bonding layer between the tungsten coating and heat sink with an intermediate thermal expansion coefficient and high compliance[12]. In the present paper, tungsten coatings of 0.2 mm thickness were deposited on copper substrate by vacuum plasma spraying (VPS) method. NiCrAl alloy and W75Cu25 composite were selected as intermediate layers because of their intermediate thermal physical performance parameters. Cyclic heat load

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experiments were performed on such coating materials. Thermal properties of the coatings and influence of cyclic heat load on the microstructure of coatings were investigated.

1 Experiment

Blocks of copper substrates were coated with NiCrAl and W75Cu25 interlayers of 0.2 mm thickness, separately at first, immediately followed by a 0.5 mm thick tungsten coating through vacuum plasma spraying technique. The difference of specimens can be seen in Table 1. Heat load tests were performed on the electron beam facility at ASIPP with the maximum electron beam power of 20 kW. And irradiation area was 20 mm×20 mm with electron beam sweeping frequency of 200 Hz. Cyclic heat load tests were carried out at a heat flux of 5 MW/m^2 with 2 s pulse duration. Surface temperature of the blocks was measured by IR and optical pyrometers. After the tests, the specimens were characterized by SEM and optical microscopy (on the surface as well as cross-section).

2 Results and Discussion

2.1 Cyclic heat load tests

Table 1 lists the main results of the electron beam cyclic heat load tests. In the case of the specimen without interlayer the results of higher surface temperature and less heat load cycles are presented. For the specimen with NiCrAl interlayer, NiCrAl intermediate layer increases the heat load cycles and displays the lower surface temperature. An important factor influencing surfacing temperature is the thermal conduction from the coating to the substrate or heat sink[13]. It is demonstrated that NiCrAl intermediate layer improves thermal conduction between tungsten coating and copper substrate. For VPS tungsten coating, failures by cracking or debonding were found after different cycles. All these failures could degrade thermal conduction and induce the surface temperature rise. So the rapid increase of surface temperature should be a signal of failure occurrence. Fig.1 shows a relationship of surface temperatures versus number of heat load cycles. As shown in Fig.1, the peak surface temperature has a sudden increase after 95, 232, and 72 cycles.

Theoretically, W75Cu25 composite interlayer can relax thermal stress during cyclic heat load tests. However, a crack crossing the irradiation area was found on the surface of VPS-W with W75Cu25 interlayer (see Fig.2). It can be concluded that thermal performance of VPS-W with W75Cu25 interlayer is worse than that of the coating with NiCrAl intermediate layer, even worse than that of the specimen without interlayer. These might be due to that W75Cu25 interlayer is too thin as an intermediate layer, or performance of W75Cu25 composite is impaired by its manufacturing process. So it can't serve effectively or relax thermal stress completely. The problems related to W-Cu composite, such as its thickness, composition and processing technique parameter should be improved further.

Table 1 Results of electron beam cyclic heat load tests

Specimen No.	W coating thickness /mm	Intermediate layer/mm	Surface temperature/ ℃	Cycles	Results
1	0.5	No	800~900	95	Failure
2	0.5	0.2 (NiCrAl)	650~700	232	Failure
3	0.5	0.2 (W75Cu25)	850~900	72	Failure

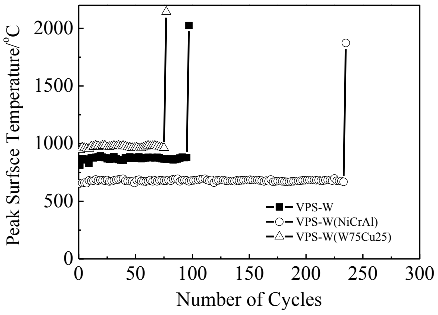

Fig.1 Peak surface temperature of VPS-W coatings vs. number of cycles

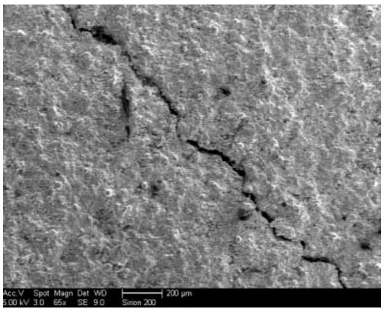

Fig.2 Surface SEM image of a cross crack on VPS-W coating with W75Cu25 as interlayer

Generally, for VPS-W coating, cracking in tungsten coating occurs more preferable to delaminating in jointing interface[14]. The crack appears during thermal heat load tests when thermal stress exceeds ultimate strength of coating. It is believed that the release of elastic strain energy as the stresses become relaxed can offer the driving force to cracking. Another fact is that strength of VPS-W coating is much lower than that of pure tungsten, and VPS-W coating cracks more easily because of its porous and heterogeneous microstructure.

2.2 Microstructure observation

Microstructure was characterized after cyclic heat load tests to identify a change or damage in the coating. Fig.3 shows the micrograph of a VPS-W coated copper substrate with W75Cu25 as the interlayer. It seems that delamination occurs between tungsten coating and W75Cu25 composite. However, no obvious exfoliation could be observed in the jointing of copper and W75Cu25 interlayer.