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Erosion and erosion products of tungsten and carbon-based materials irradiated by a high energy electron beam

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Abstract

A pulsed electron beam test was used to simulate the thermal response of plasma facing materials under high heat loads during plasma disruptions, particularly for relatively 'long' duration off-normal events such as plasma vertical displacement events. The erosion and erosion products of purified tungsten made by powder metallurgy (PM-W), W and B_4C plasma sprayed coatings on CFC or copper and C/C composite were investigated. The time evolution of the target current indicates that the erosion products or screening clouds partly or completely shield the incident electron beam, leading to a reduction of the target current and changes in the target current profile. The weight loss of PM-W is smaller than that of the tungsten coating or C/C composite, which is in agreement with the erosion behavior. Erosion products indicate that evaporation is a major erosion mechanism of PM-W, and exfoliation and particle emission are the dominant erosion mechanisms of carbon-based materials and W plasma sprayed coatings.

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Keywords: Erosion; Erosion products; VDE; PM-W; W and B4C coatings; C/C composite

1. Introduction

High *Z* and low *Z* materials are both envisaged as candidate plasma facing materials (PFMs) of fusion devices. Tungsten is a typical high *Z* material, and graphite, C/C composite and beryllium are typical low *Z* materials. These low *Z* materials have been successfully used as PFMs in current fusion devices. In particular, C/C composite are commonly used as high heat flux components. Tungsten (purified W and W coating) limiter/divertor tile experiments have been performed or scheduled in ASDEX Upgrade and TEXTOR [1]. During off-normal plasma operation conditions, the surface of these materials or components receives a high heat flux. Therefore, severe damages of materials such as melting, evaporation and fracturing occur. These processes reduce the lifetimes of these components and shorten the continuous operation time of fusion devices. On the other hand, the re-deposition of erosion products on the wall or the penetration of erosion products into the core plasma affects the properties of materials and impurity level of the plasma, respectively.

There are three main patterns of off-normal operations in tokamaks: hard disruptions, edge-localized modes and vertical displacement events (VDEs). Of these VDEs have the greatest capability to damage PFMs. Generally, when VDEs occur, the deposition energy density (full power) is up to 100 MJ/m^2 and the energy deposition time is 100–300 ms [2]. Electron beam or ion

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beam experiments have been often used to simulate the thermal responses of PFMs and components during normal or off-normal operation events. Although many investigations on the erosion and erosion products corresponding to a transient heat load for graphite and C/C composite have been conducted [3–5], there are only few publications concerning the erosion products of PM-W and coating materials such as tungsten and B_4C coatings. As the examples, the splashing of a tungsten melt layer under an extremely high heat load [6] and the preferential evaporation of B or Si impurities from carbon-based materials (CBMs) were reported [7]. In this paper, the erosion behavior and erosion products of PM-W, tungsten coatings, C/C composite and B_4C coating on copper with transition interface layers, were investigated by using a pulsed electron beam to simulate the heat load of a VDE. In this work, we focussed on examining the differences in erosion products among these testing materials, and on clarifying the erosion mechanisms.

2. Experimental

The high heat load test and collection of erosion products were performed at a high energy electron beam facility. The details of the facility can be found in a previous publication [8]. In the present experiment, a 60 keV electron beam with a current of 20–50 mA and a pulse duration of 1 s was used. The spot of the electron beam was 3–3.2 mm in diameter with the shape of a slight ellipse. The current of the incident electron beam was measured by a Faraday Cup (FC) with a target plate of purified tungsten. The incident peak power density was controlled in the range 170–340 MW/m^2 by adjusting the current of the electron beam. A single-crystalline silicon plate was placed at one side of the sample with an angle of 45° to the sample surface in order to collect the erosion products [8]. The silicon collector was polished like a mirror and the size was $20 \times 15 \times 2$ mm. Collected erosion products were observed by scanning electron microscopy (SEM), and their chemical compositions were analyzed by energy dispersion X-ray spectroscopy (EDS). Testing materials were purified tungsten, PM-W (99.95%, made by Northwest Institute of Non-Ferrous Metals, China), tungsten coating on CFC (W/CFC – CX-2002U) and on copper (W/Cu), 3D-C/C composite and B_4C coating on copper with transition interface layers (B_4C/Cu). PM-W was made by powder sintering and shaped by rolling with a final thickness of 2.5 mm. The sample size of PM-W and the C/C composite was $12.5 \times 12.5 \times 2.5$ mm. The thickness of the W and B_4C coatings was 0.4–0.5 mm, and the coating samples (W/CFC, W/Cu and B_4C/Cu) had a thickness of 4 mm. The W/CFC sample was made by vacuum plasma spraying with a rhenium diffusion barrier [9]. The W/Cu and B_4C/Cu samples were made by inert gas plasma spraying [10].

First, all samples were mechanically polished except the coating samples, and then supersonically cleaned and degassed at 250 °C for several hours. Before electron beam heat load tests, all samples were exposed to an environment with a constant temperature and humidity for 24 h, and then weighed by an electron balance with 0.1 μg sensitivity. After electron beam irradiation, the sample was extracted from the vacuum chamber, and weighed by the same method again.

3. Results and discussion

3.1. Electric current profiles of time evolution

Before electron beam heat load tests, the spatial distribution of the electron beam was measured by a FC, showing a Gaussian-like distribution. In the present experiment, an electron beam with a diameter from 3 to 3.2 mm was employed. The incident current and target current were measured by an AD board with 4 kHz speed before and during the irradiation experiment, respectively. Fig. 1 shows the time evolution of the incident current measured by an FC, current without an FC, and target currents of PM-W and C/C composite specimens. From Fig. 1, it is seen that the pulse duration of the electron beam is about 1 s with a 300 ms half width. In order to measure the influence of the electron reflection and the secondary electron emission on the target current, and to avoid shielding effects, a defocused electron beam (about 15 mm in diameter) was used in the case of an incident current measurement without an

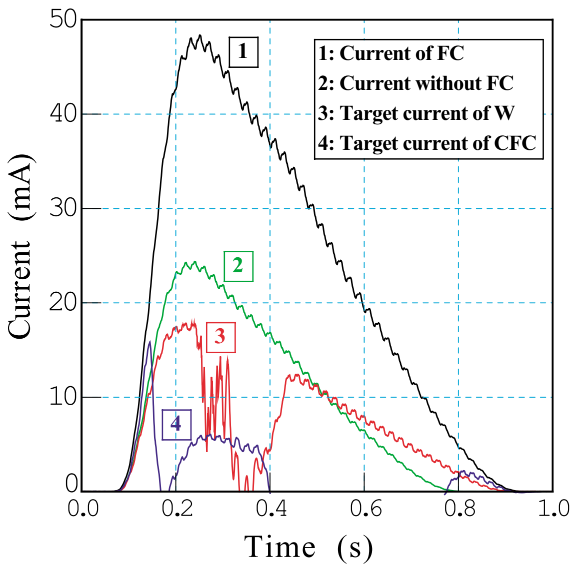

Fig. 1. Electron beam current for cases with an FC, without an FC, and targets of W and CFC.

FC. In the case without an FC, it is seen that the net target current was greatly reduced by the reflection and secondary electron emission. But the current profile remained roughly the same. The shapes of the target currents of the PM-W and the C/C composite have been remarkably changed. An oscillation of the target current was found in the case of PM-W, and the target current became zero in the time period of approximately 400 ms. In the case of C/C composite, the target current became zero in the time periods of 200 ms and 400–800 ms. One reason for changes of the absorbed target currents is the shielding of the incident electron beam by erosion products emitted from the sample surface. In the case of C/C composite, the electron beam was screened completely during a relatively long time period. Fig. 2 shows the target currents of C/C composite with and without a Si collecting plate. The reduction of the target current by the shielding effect may be partly compensated, since the Si plate receives part of the scattering electrons by shielding clouds. For the case of the Si plate shown in Fig. 2, the target current profile became close to the profile of the incident electron beam. A similar phenomenon has been previously reported [2,11].

3.2. Weight loss and surface damage

Fig. 3 shows the weight loss of the tested materials for a single electron pulse irradiation. It is seen that the largest weight loss is found for C/C composite and the weight loss of PM-W is rather small compared with that of C/C composite or W/Cu coating. In fact, no obvious damage for PM-W was observed when the peak heat flux of the incident electron beam was lower than 250 MW/m^2. W/Cu sample was made by plasma spraying using a tungsten particle with a size of 30–40 μm. This material may have high porosity and a relatively weak bonding strength. SEM observation indicated that the tungsten coatings on the center of the electron beam spot (about 1–2 mm diameter) were almost completely peeled off except for the irradiation experiment with the lowest beam current. In addition, particle emission was clearly seen during electron beam irradiation as reported in Ref. [11]. When the peak heat flux of the incident electron beam exceeded 280 MW/m^2, melting and recrystallization were observed on the surface of PM-W samples. Consequently, in this case the peak surface temperature should have been higher than 3410 °C.

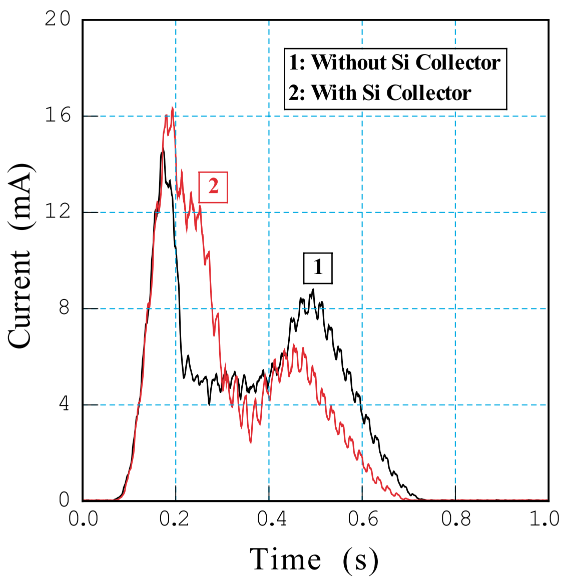

Fig. 2. Electron beam current for cases with and without an Si collector.

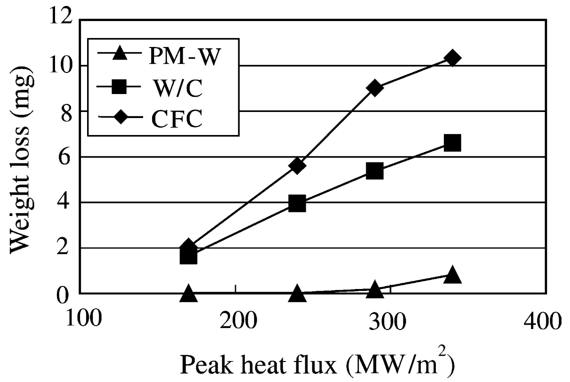

Fig. 3. Weight loss of PM-W, W/Cu coating and C/C composite versus peak heat flux.

3.3. Erosion products

PM-W: For purified tungsten made by powder metallurgy, erosion mechanisms were melting and evaporation when the peak heat flux of the incident electron beam was higher than 280 MW/m^2. Fig. 4 shows the

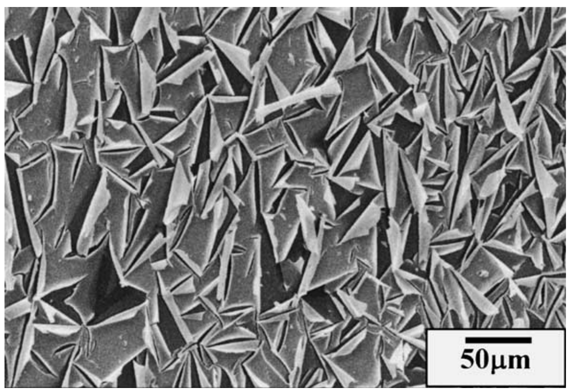

Fig. 4. Erosion products of PM-W irradiated by a pulsed electron beam (340 MW/m^2, 1 s).

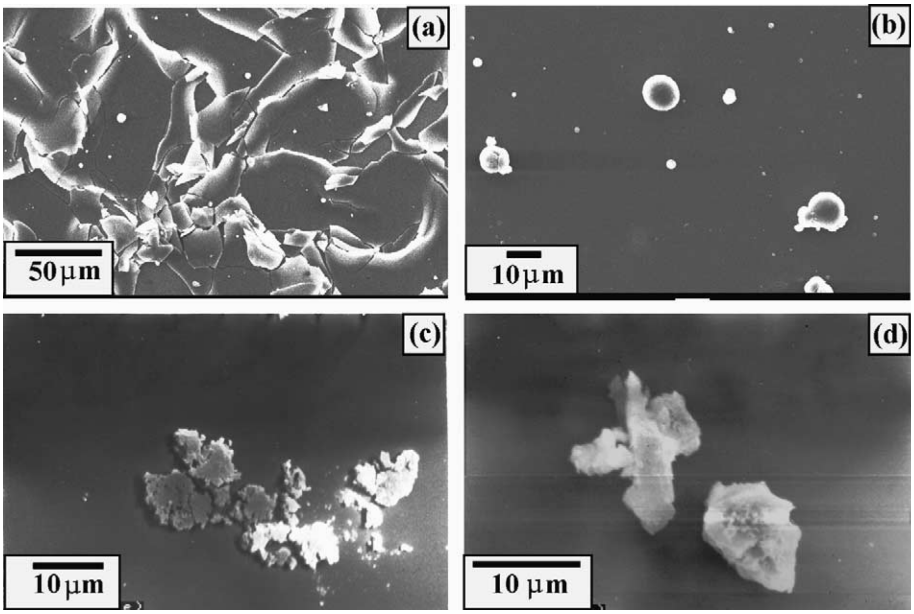

Fig. 5. SEM images of erosion products for B_4C/Cu (a) and (b), and for W/CFC (c) and (d).

erosion products of PM-W after one pulsed electron beam irradiation with a peak heat flux 340 MW/m^2. The deposition of tungsten vapor was observed, and splashing of melted tungsten was scarcely found. The block-like structure of deposited tungsten may be produced by the shrinkage of coagulated evaporation layers during cooling.

W and B_4C coatings: Erosion products were observed for W and B_4C coatings as shown in Fig. 5. Fig. 5(a) and (b) are SEM images of the erosion products of B_4C/Cu after one electron beam irradiation with a peak heat flux 170 MW/m^2. The deposition appearing in Fig. 5(a) is due to the evaporation of boron and carbon. The particle deposition appearing in Fig. 5(b) corresponds to B_4C particle emission from the coating surface. The atomic concentration of the particle was measured by EDS and the atomic ratio, B/C, was about 2.8. Fig. 5(c) and (d) show the erosion products of the W/CFC sample after the irradiation with a peak heat load of 280 MW/m^2. The products obviously result from the exfoliation of the tungsten coating and corresponding particle emission. For CBMs such as B_4C, it is believed that particle emission is the main erosion mechanism [4,12]. In the present experiment, depositions of carbon and boron were also observed. The reason for this may be the evaporation of emitted particles by the incoming electron beam. The sizes of the collected particles (shown in Fig. 5(b) and (d)) were close to the sizes of the sprayed particles on the surface of W or B_4C coatings, respectively. It is thought that exfoliation and particle emission of W and B_4C coatings made by plasma spraying under high heat loads could be due to weak bonding of the sprayed particles. This is also the essential reason for the tungsten coating showing a larger weight loss than PM-W as shown in Fig. 3.

C/C composite: In the erosion products of C/C composite, some individual fibers were found (as shown in Fig. 6), which resulted from brittle destruction of C/C composite caused by thermal stress. This is a dominant erosion process in the present experiment. A relatively high fraction of carbon fiber segments-individual fibers as well as small fiber clusters have been observed by Linke et al. in the carbon dust of TEXTOR and in electron beam load tests of C/C composite [3,13]. In fact, preferential erosion of carbon fibers of this kind of

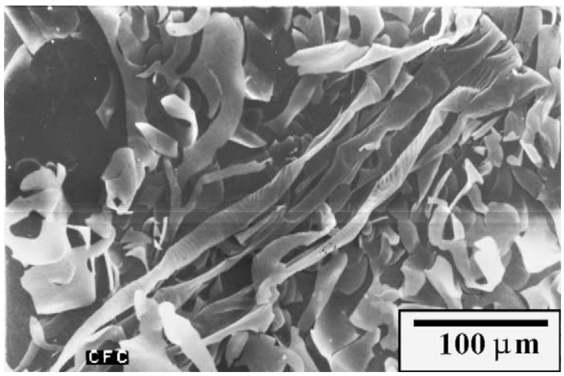

Fig. 6. Erosion products of C/C composite by a pulsed electron beam (170 MW/m^2, 1 s).

3D-C/C composite was also found in the HL-1M tokamak of China [14].

4. Conclusions

Electron beam heat load tests for PM-W and tungsten coatings, as well as C/C composite and B_4C/Cu coating, were carried out to simulate the thermal response of these materials under high heat load condition corresponding to VDEs. Their erosion products were collected by single-crystalline Si plates. First, the time evolution of the target current indicated clearly that the emission of erosion products influenced the incident electron beam by the shielding effect. Second, the weight loss of PM-W was much smaller than that of the tungsten coating or C/C composite. C/C composite had the largest weight loss.

Based on the investigation of the erosion products, we conclude that evaporation is a major erosion mechanism of PM-W, and exfoliation and particle emissions are the dominant erosion mechanisms of W and B_4C plasma sprayed coatings. These effects are also the essential reason for the larger weight loss of the tungsten coating compared to that of PM-W under the same heat load conditions. For C/C composite, erosion by sublimation or evaporation of carbon has been observed. However, the dominant erosion process was large particle emission due to brittle destruction of CBMs. In this case, individual carbon fibers were found in the erosion products.

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