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2. 5 The Erosion and Erosion Products of Tungsten and Carbon Based Materials Bombarded by High Energy Pulse Electron Beam

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Key words: Thermal erosion, Erosion products, VDE

High *Z* and low *Z* materials are both the candidate plasma facing materials (PFM), up to now, the typical representative of high *Z* materials is tungsten, and the representatives of low *Z* materials are carbon materials (such as graphite, C/C composite) and beryllium. Most of these materials have been used as PFM limiters and diverter armor tiles of tokamak machines; tungsten, molybdenum and C/C composite are always used as high heat flux components. During tokamak machine operating, especially under off-normal operation conditions, great thermal load will be deposited on the surface of these components, serious damages, such as evaporation, melting and fracturing could be occurred, which will reduce the lifetimes of these components and shorten continuous operation times of tokamaks. On the other hand, the redeposition or entering the core plasma of erosion products will also influence both the properties of materials and core plasma.

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There are three main patterns for off-normal operation condition of tokamak plasma, they are hard disruptions, edge location modes (ELM) and vertical displacement events (VDE), in which VDE have the greatest destructive power. Generally, when VDE occurred, the deposition energy density (full power) is more than 100 MW • m^{-2} with 0. 1 to 1 s pulse time [1]. Nowadays, many investigations on the erosion and erosion products for graphite and C/C composite have been reported, but few papers concerned to the erosion products of tungsten and carbon-based materials[1], especially coating materials, such as tungsten coating and B_4C coating. In this paper, the erosion behaviors and erosion products of tungsten (samples made by powder metallurgy and plasma spraying) and some carbon based materials, such as graphite, C/C composite and B_4C/Cu functionally graded material, were investigated by using a pulse electron beam to simulate the VDE process, the authors will focus on the forms and differences of erosion products among these testing materials, and make clear to their erosion mechanisms.

1 Experiment

The thermal load and collection experiments of erosion products were performed by a high energy pulse electron beam in a chamber with about 10^{-1} Pa pressure, the details of the facility can be reference to a previous paper[2]. In present experiment, a 60 keV electron beam with 20 to 50 mA current and a slight ellipse of 3~3.2 mm diameters was adopted, the pulse time was 1 s with about 300 ms half-wide, incident energy density was controlled in the range 170~340 MW • m^{-2}, the collection plates are made of single crystal silicon with a size of 20 mm×15 mm ×2 mm and set up at the sample by an angle of 45° with the surface of samples[2]. The testing materials are purity tungsten PM-W (99.95%, made by Northwest Institute of Non-Ferrous Metals, China), coating on graphite and copper W/C or W/Cu, 3D-C/C composite and B_4C/Cu functionally graded materials. PM-W was made by powder sintering and shaped by rolling with a final thickness of 2.5 mm, so the sample size of PM-W and C/C composite is 12.5 mm×12.5 mm×2 mm, but the coating samples (W/C, W/Cu and B_4C/Cu) have 4 mm thickness, the thickness of coating are 0.4~ 0.5 mm for tungsten and 0.8 mm for B_4C, they are both prepared by vacuum plasma spraying (VPS) and inert gas plasma spraying (IPS).

Before moving into vacuum chamber, all samples were mechanically polished except the coating samples, supersonically cleaned and degassed at 250 ℃ for several hours, then weighted by an electron balance with sensitivity of 0. 1 μg. After electron beam irradiation, the sample was firstly weighted and then analyzed by scanning electron microscopy (SEM) and energy dispersion X-ray spectroscope (EDS).

2 Results and discussion

2. 1 Electric current profiles of time evolution

Before electron beam irradiation on the samples, the profile of electron beam was measured by a Faraday cup (FC), which is a slight ellipse of 3 to 3.2 diameters with a Gaussian distribution. The time evolution target current was also measured by a collector before of during irradiation experiment. Fig. 1 shows the time evolution of target current measured by FC and without FC on the case of defocusing, PM-W and C/C composite under focusing. Comparing target current with and without FC, it can be seen that the secondary electron and hot electron emission, as well as reflections of incident electrons greatly reduce the net target current but don't significantly change its shape. However, from the current profiles of PM-W and C/C composite, it can be seen that the shapes of target currents have been changed greatly. For PM-W, firstly, the target current gradually rose with incident electron increasing, when incident current reached to maximum value, an oscillation appeared, after that, the target current rose gradually again, then slowly decreased. For C/C composite, the target current decreased sharply to zero even before the incident electron beam reached to maximum value, because the incident current still increased, the target current gradually increased again and went down to zero for about 400 ms, then increased again, finally ended with incident electron beam stopping. One main reason is that the emissions of erosion products or the formation of screening clouds partly obstruct to the incident electrons, in some case such as parts of the irradiation times for C/C composite, the electron beam was screened completely. Fig. 2 is another example about shielding effect, which shows target current profiles of C/C composite with and without Si collecting plate, owing to Si collecting plate electrically contacting with sample, reduction of the target current of C/C composite sample by shielding effects will be partly compensated since parts of the electrons obstructed could be received by Si plate for the case with Si collector, therefore, the target current profile with Si collector will be more close to the common profile of incident electron beam. Similar phenomenon has been observed in Ref. [3].

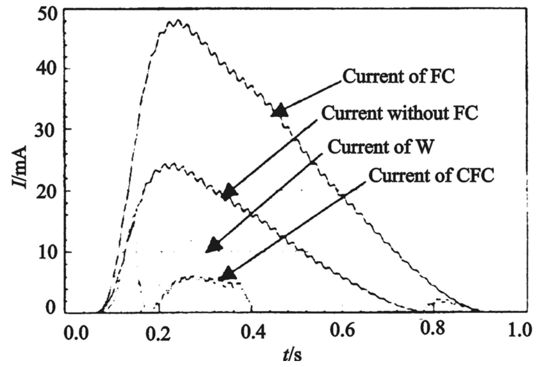

Fig. 1 Current profile of time resolution for incident electron beam and W and C/C composite targets

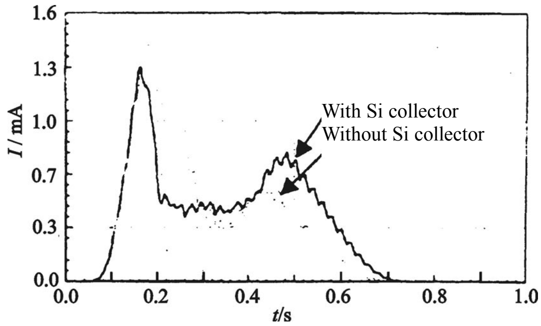

Fig. 2 Target current of C/C composite with and without Si collector

2. 2 Weight loss and surface damage

Fig. 3 shows the weight loss of testing materials for single electron pulse irradiation, it can be seen that C/C composite has largest weight loss and the weight loss of PM-W is rather small comparing with that of C/C composite and W/Cu coating. In fact, there is almost no any obvious damage to be observed for PM-W when energy density is lower than 250 MW • m^{-2} meanwhile the target current shapes are nearly no change, which implies there aren't many tungsten particles emission from the surface on these conditions. For W/Cu coatings, almost all tungsten coatings on the center (about 1 to 2 mm diameter) of the electron beam irradiated zone peeled off completely except for the case of the lowest energy density. When incident energy density is beyond 280 MW • m^{-2}, melting and re-crystallization can be found on the surface of PM-W samples, the erosion mechanism will be discussed in next section.

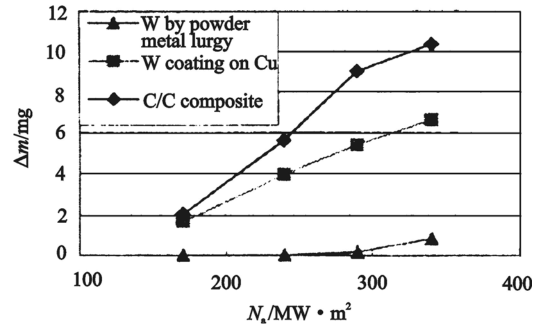

Fig. 3　Weight loss of testing materials vs energy density of incident electron beam with about 300 ms pulse halfwide

2. 3　Erosion products

PM-W: for purity tungsten made by powder metallurgy, main erosion mechanism is evaporation, its erosion product by single pulse electron bombardment with 340 MW • m^{-2} energy density indicated that the block-like structure came from the shrinkage of coagulated evaporation tungsten during cooling, usually, the adhesion properties between substrate Si plate and deposition layer, especially when substrate Si plate isn't at elevated temperature just like the case of this experiment, therefore, parts of deposition layers have separated from the Si plate.

W/Cu and B_4C/Cu coatings: besides the evaporation of tungsten or boron and carbon as mentioned above, which usually located on the center parts of the deposition zone. Some resolidified separation dots were also observed on the edge of deposition zone where the deposits is also rather lesser than that of the center zone. EDS measurements indicated that the circular deposits of W/Cu consisted of W_xO_x in which oxygen could come from bad vacuum circumstance (only 10^{-1} Pa during electron beam irradiation), and the circular dots in the case of B_4C/Cu coating should be correspond to B_4C particles because of its atom concentration ratio B/C is 2. 8. On the other hand, the sizes of these deposits are closely corresponding to the sizes of tungsten and B_4C particles, respectively. Since these erosion products only appeared on the outer edge of deposition zone where the deposits will request the largest emission angle, meanwhile, considering the erosion crater of the inverted triangle, a reasonable explanation seems to be that only the emission particles on the edge of the electron beam irradiated zone with the largest emission angle have a choice not to be evaporated before they reached to Si collector in the initial stage of electron irradiation. Although most of scientists believe that particle emission could be main erosion mechanism of carbon based materials and coatings due to brittle destruction and weakly strength of the grain boundary[4], respectively, although direct observations are hardly reported. In present experiment, we at least supplied a powerful evidence to particle emission of coatings.

C/C composite: like the coating materials, two kinds of erosion products were found, one came from the evaporation of C/C composite, and the other displayed the structure of carbon fibers which should result from brittle destruction of carbon materials, it located on the edge of deposition zone too.

According to the weight increment of Si plate, it can be estimated that the average thickness of deposition zone is 1~2 μm, the maximum thickness is about 3~4 μm and the thickness reduced with increasing of particle emission angle.

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2. 6 The Brittle Fracture Mechanism of Vanadium Alloy with High Level of Oxygen and Hydrogen

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Key words: Vanadium alloy, Hydrogen embrittlement, Oxygen effect

Hydrogen embrittlement is one of the key issues for the vanadium alloys for fusion application[1]. Previous study has shown that V4Ti alloy had better properties against the embrittlement than V4Cr4Ti and V4Ti3A1 alloys[2]. It was thought that