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ABSTRACT

Using the DiMES mechanism at DIII–D, erosion rates of graphite, and metallic coatings of Be, V, Mo, and W have been measured under different plasma operating conditions. The measured net erosion rate for C is substantial (16 nm/s) during ELMing H–mode at a heat flux of 2 MW/m^2. Measured gross erosion rates of the metals are lower than expected from sputtering yields, most likely due to heavy surface contamination by carbon. The measured erosion of W is substantially lower than the other materials, and when account is taken for redeposition, it is shown to be a viable candidate for the Starlite reactor's divertor.

I. INTRODUCTION

Surface material erosion due to plasma-material interaction will limit the performance and lifetime of tokamak plasma facing components, particularly in the divertor, where large incident particle and heat fluxes and high material surface temperature are expected. The erosion phenomenon is a complex process involving: gross material losses due to physical and chemical sputtering, sublimation and evaporation, redeposition due to plasma transport of ions back to the surface, and surface reactivity with plasma contaminants. The material re-deposition fraction at the divertor can be expected to be quite high, therefore it is important to study net erosion in a tokamak device. Additionally, high power flux due to transient events such as edge localized mode (ELMs), disruptions and arcing may enhance sputtering erosion and cause surface melting and bulk material transport. The main purpose of the Divertor Material Evaluation System (DiMES) program at DIII–D is to measure erosion rates and study redeposition mechanisms under tokamak divertor plasma conditions in order to obtain an integrated physical understanding of the erosion/redeposition processes.[1] This paper reports measured results from DiMES under various operating conditions, including ELMy plasmas, and discusses the implication of these results to the Starlite fusion power plant plasma facing component design.

II. THE DiMES APPARATUS, OPERATION AND PLASMA DIAGNOSTICS

The DiMES apparatus allows insertion and retraction of test samples to the DIII–D divertor floor.[1] Samples consist of ATJ-type graphite, polished to a 0.25–1 μm finish on their plasma facing side, which is aligned to within 0.25 mm to neighboring tiles. The outer strike point of the plasma can be programmed to be located on the sample after the desired plasma is established. Different plasma discharges with various neutral beam power inputs, with or without ELMs have been studied. The divertor plasma is well characterized by a series of diagnostics, including Langmuir probes, infrared thermography and CCD camera which are used to obtain radial profiles of the ion flux, electron temperature and density, and surface temperature. Magnetic geometry, including the position of the separatrix and the magnetic field pitch angle, are derived from the magnetic reconstruction code EFIT.[2] In-situ erosion observations are also derived from the brightness of carbon and beryllium spectral line emissions, and the colorimetry technique.[3] The location of DiMES in DIII-D and various diagnostics is given in Fig. 1.

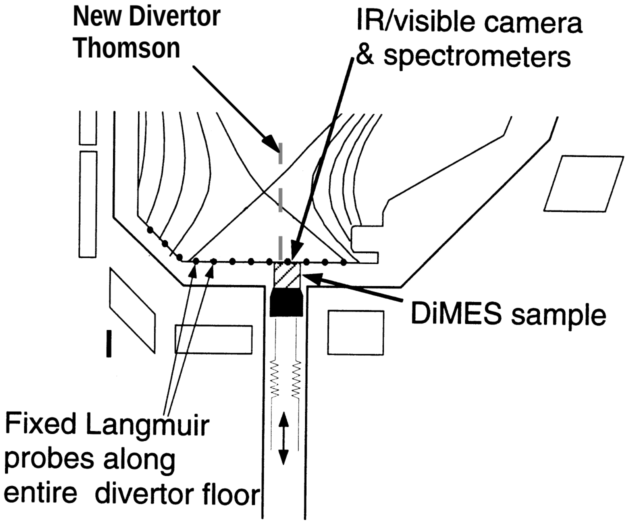

Fig. 1. DiMES exposure and diagnostic coverage at DIII–D.

III. EROSION STUDIES UNDER NORMAL OPERATION

During the past two years, several DiMES graphite samples with and without metallic coatings were exposed to various plasma discharges at the divertor floor of the DIII–D tokamak. The first wall of DIII–D is dominately graphite (>90% coverage), and carbon is the dominant plasma impurity.

A. Erosion Experiments

Of particular interest for this paper are five plasma experiments in which DiMES samples were exposed to the outer divertor strike point plasma with the plasma in a lower single-null configuration: 1) the sample designated as DiMES 8 has a 1 cm diameter tungsten coating on a ATJ graphite sample, was exposed to six shots of ELM-free H–mode outboard strike point for a total exposure time of 13.5 s; 2) DiMES sample 70 has alternating squares (7.5 × 7.5 mm) of V and Mo coatings, spaced radially at the toroidal center of the samples. This sample was exposed to six ELM-free H–mode discharges with a total exposure time of 14 s. 3) DiMES sample 71 has alternating squares (7.5 × 7.5 mm) of Be and W coatings, spaced radially at the toroidal center of the sample. This sample was exposed to three shots of ELM-free H–mode with a total exposure time of 4 s. 4) DiMES sample 40 was a ATJ graphite sample with an amorphous layer of carbon, exposed to ELMing H–mode plasma for 9 shots with a total exposure time of 8 s. 5) The DiMES sample 74 has a radial stripe (3 mm × 32 mm) of W offset 10 mm upstream and another stripe of Be offset 10 mm downstream from the sample's toroidal center. It was exposed to four discharges of ELMing H–mode plasma with a total exposure time of 13 s. Exposure parameters of these experiments and corresponding erosion rates of exposed materials are presented in Table 1.

B. Erosion and Redeposition Measurements

Ion beam analysis was performed on the samples before and after exposure. Net erosion of carbon is measured using an implanted Si depth marker to a depth resolution of ±10 nm. Erosion of thin metallic coatings (100 nm thick Be, V, Mo, and W) and their redeposition on the neighboring graphite surface is measured by a combination of Rutherford Backscattering Spectroscopy (RBS) and Nuclear Reaction Analysis (NRA). The gross erosion of metallic coatings is estimated from reduction of the original film's thickness and by integrating the redeposited areal concentrations. As an example, for a 5% total W film erosion, the direct measurement and the integration technique agree to with 20%, validating the measurement techniques and indicating that most of the original W (99%) remains on the sample.[4,5] Measured net (carbon) and gross (metals) erosion rates are presented in Table I. It is clear that the erosion rate of carbon and metallic coatings increases with heat flux. When comparing results of metallic coatings Be, V and W, they show that the erosion rates for these metal films decreased with increasing atomic number. The areal concentration of metal deposited onto neighboring carbon surfaces decreases exponentially with distance from the metal film. The e-folding length also decreases with atomic number.[6] These results suggest a high local deposition for eroded high-Z metallic elements.

Sample 71 with Be and W coatings, exposed to 0.7 MW/m^2 heat flux in ELM-free H-mode has a peak carbon erosion rate of ~4 nm/s. This matches quite well with vigorous impurity transport modeling calculation.[7] The metal’s deposition profiles match quite well with impurity transport code calculations. At a higher heat flux of 2 MW/m^2 and with the additional impact from ELMs, DiMES 74 shows a carbon erosion rate of 16 nm/s.[6] However, these results were obtained under condition of

Table 1
Exposure Conditions & Erosion Rate for Samples 8, 70, 71, 40, and 74 Exposed to H–Mode Plasma

(Typical global plasma parameters of interest are: gas = D_2, I_p = 1.35–1.4 MA, B_T = –1.9 T, magnetic pitch angle at OSP = 1.5–2.5°, Z_{eff} = 1.5, carbon fraction in core =1–2%, oxygen fraction in core = 0.1–0.2%). T_e at OSP from fixed floor Langmuir probes.

					Erosion Rate (nm/s)				
DiMES Sample No.	ELMing	Heat Flux (MW/m^2)	T_e (eV)	Surface Temperature (°C)	C	Be	V	Mo	W
8	No	0.45	NA*	<200	4				0.06
70	No	0.7	70	60–100	3.6		0.5	0.3	
71	No	0.7	70	60–100		0.9			0.1
40	Yes	1.1	35	<150	9				
74	Yes	2.0	45	200–300	16	1.4			0.45

*Not available.

enhanced C deposition due to a misaligned tile adjacent to DiMES. Arc tracks were clearly observed on the W-coated surface, which may contribute to additional erosion.[6] The cause and effect of these arc-tracks are under investigation.

IV. IMPLICATIONS FOR ITER DESIGN

For the 1996 ITER-EDA divertor design that uses a combination of C, Be and W materials, one of the outstanding issues is the erosion behavior of these materials under various ITER operating conditions. DiMES measured and modeled results can provide some integrated exposure indications.

A. Carbon Erosion

For carbon under ELM-free H–mode conditions, the computer simulations[6,8] show both gross and net erosion rates peaking at the separatrix, a peak net rate of ~1/5 of the gross rate (i.e. 80% redeposition rate), and a region of net growth resulting from radial transfer of sputtered carbon. This redeposition rate is lower than the 90% value used for ITER lifetime calculations.[9] From the ELMing H–mode exposure of DiMES 74, with a surface heat flux of 2 MW/m^2, an erosion rate of 16 nm/s was measured. This exposure environment appears to be similar to the operating conditions of one of the example conditions of ITER (2.5 MW/m^2, 250°C, T_e = 50 eV, core Z_{eff} = 1.5), for which a net sputtering loss rate of 2 nm/s was projected. Note that for this comparison, an obvious difference in the plasma conditions is the presence of ELMs in the experiment, which could enhance transport of the eroded material and increase net erosion. However, the 0.7 MW/m^2 ELM-free carbon erosion rate of 4 nm/s also exceeds the ITER projection. Clearly, further measurements of carbon erosion, under a variety of plasma conditions, are needed in order to extrapolate these results reliably to ITER and understand the effect of ELMs on net erosion.

B. Beryllium Erosion

For beryllium, we find that the measured gross Be erosion rate for DiMES 74 is 1/4 of the physical sputtering VFTRIM calculated erosion rate for D^+ sputtering.[8] In the DIII–D divertor carbon is continuously deposited on the Be surface at a high rate and affects the Be erosion. The formation of a mixed C-metal surface layer has been offered an a possible explanation for this reduction of net erosion of Be.[10] Such effects may be important for modeling a multispecies environment like that of the ITER divertor.

C. Tungsten Erosion

For tungsten, DiMES 74 exposed under ELMing H–mode conditions shows a gross erosion rate of up to 0.45 nm/s and a redeposition e-folding length of ~4 mm. With a carbon coating or a mixed W and C surface layer, we expected a reduced erosion rate from that of pure W.[4] As mentioned before, arc-tracks are clearly observed on the W coating surface after exposure. The cause and erosion/redeposition contribution of this arcing process needs further examination.

V. IMPLICATIONS TO THE STARLITE FUSION POWER PLANT DESIGN

A. Materials Selection

The U.S. Starlite Fusion Power Plant Design[11] is a steady state device with an electrical output of 1000 MW. To achieve the design goals of low activation and fusion power core components life time of 2.5 full power year, the preferred divertor structural, and plasma facing materials are V-alloy and W-coating, respectively. In addition to the low activation property, V-alloy was selected because of its higher temperature capability than other metallic structural materials under the fusion environment and its compatibility with lithium which is the tritium breeder and blanket/divertor coolant of the Starlite design. W was selected as the plasma facing coating because of its higher value of heat of sublimation and a high threshold for sputtering which is above 100 eV when monoenergetic hydrogen species is the impinging ions.

Materials like graphite and Be are projected to be not suitable for fusion power plant design because of the concerns on the degradation of the thermal and mechanical properties due to high neutron fluence, in addition to the issue of relatively high erosion rate. The latter is supported by the relative results in Table I.

B. Results From DiMES and W Erosion

Comparing, Table I shows that under similar discharge conditions, W has 1/5 the gross erosion rate of V. The difference is lower than expected from hydrogen sputtering, this may be due to sputtering by carbon impurities in the plasma. Nevertheless, more study on the erosion of V-alloy will be needed when it is potentially the plasma facing material for the Starlite first wall design.

Even though DiMES has provided erosion rate results for metallic coatings, they are indicative of gross erosion rates rather than net rates, since the metallic coating surface area is relatively small and the DIII–D is a graphite machine. Therefore, one cannot simply extrapolate erosion rate results from DiMES to Starlite conditions. On the other hand, interesting W erosion observations can be made based on the measurement of deuterium ion temperature. Preliminary results from another DiMES probe, which estimates the divertor ion temperature from implanted charge exchanged D in Si,[5] show that the divertor ions have an average energy of ~100 eV. If this ion temperature is applied to the Starlite design, the physical sputtering yield of W, based on Eckstein's TRIMSP[12] computer modeling using a Maxwellian distribution of ion energy and including sheath potential at room temperature, are 10^{-3} and 4×10^{-3} for deuterium and tritium, respectively. At an ion flux of 9×10^{22} m^2/s, the gross physical erosion rate from the burning of D and T is 2.9 nm/s. This would correspond to a lifetime of 193 h for a divertor W-coating thickness of 2 mm, which is not acceptable when compared to a design goal of 2.5 years (21900 h). This is indicative that in addition to high redeposition rate, we may also have to rely on the reduction of ion maximum temperature to below the physical sputtering threshold of 25 eV. This requirement can be satisfied with the approach of radiative divertor, where maximum electron temperature in the range of 10 to 20 eV has been measured in DIII–D.[13] At this temperature, net erosion rates for typical reactor conditions are very low, e.g., $\lesssim 0.02$ cm/burn-yr[14] on tungsten erosion. This supports the possibility of using W as the divertor coating material for the Starlite solid target divertor design. This projection should be further verified by detail modeling and experimental efforts.

C. Other Issues From the Use of W

With the consideration of redeposition and radiative divertor approach to reduce the ion temperature, we have indicated the possibility of using W as the Starlite divertor coating material. It should be noted that the effects from W self-sputtering and additional sputtering from V ions in a V first wall machine, i.e, V-alloy background, have not been considered. In addition to sputtering there are also the concerns of high-Z core contamination from the migration of W ions from the divertor and the spread of W particulates to the first wall under disruptive events. The surface reactivity of W-metal with plasma contaminants such as oxygen and carbon must also be considered. However, recent favorable results from ASDEX-Upgrade show that the migration of W from its divertor is acceptable which is encouraging.[15] As indicated above, potential erosion contribution from the arcing of W-surface will also have to be investigated.

VI. CONCLUSIONS

DiMES has successfully measured the erosion rate of candidate PFC materials under real tokamak conditions in the DIII-D divertor. Preliminary scaling studies show that the erosion rate of the surface material increases with heat flux and the introduction of ELMs. Under ELMing conditions, the measured carbon erosion rate is substantially higher than estimated for ITER under ELM-free conditions. On the other hand, the erosion rate of Be is about 1/4 of the calculated predicted sputtering rate. This reduction in Be erosion may be caused by the background of carbon and needs further investigation. The measured gross erosion rates of metal films is seen to decrease as the atomic mass of the metal increases. The results for W, when account is taken for redeposition in a full W divertor environment, indicate that it is a suitable divertor plasma-facing material for Starlite if a radiative divertor plasma can be used to reduce T_i below 20 eV at the strike point. Further impacts from self-sputtering and sputtering in a V background machine will have to be considered. Impacts from high-Z migration, disruption and surface arcing will have to be evaluated.

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