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Erosion mechanisms and products in graphite targets under simulated disruption conditions

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Abstract

Plasma/material interaction was studied in disruption simulation experiment at plasma gun facility MK-200 UG. Graphite was exposed to intense plasma stream under heat fluxes typical to ITER hard disruption. Plasma-induced surface damage and carbon erosion products were analysed.

1. Introduction

Erosion of carbon-based divertor plates under ITER disruption conditions [1] (i.e., 10–100 MJ/m^2, 1–10 ms) represents a serious challenge and poses lifetime limitations. Erosion restricts the divertor lifetime and leads to the production of tritiated carbon dust, which is one of the major safety issues for future fusion reactors.

An understanding of the erosion rate and of the amount of dust expected in ITER and its physical and chemical characteristics is required to verify assumptions currently used in ITER erosion and safety analysis. Since the disruptive heat loads typical for the next-step fusion reactors are not achievable in existing tokamaks, plasma/material interaction must be investigated in powerful plasma devices capable to simulate, at least in part, the loading conditions of interest for disruption damage.

Experimental and theoretical investigations [2] have shown that disruptive heat flux results in a sudden evaporation of a thin surface layer of the irradiated material and produces a cloud of dense target plasma. The target plasma acts as a thermal shield protecting the surface from further excessive evaporation. The incoming energy flux is dissipated mainly into radiation of target plasma. Due to the vapor shielding effect, the real heat load on the surface and therefore, the erosion rate decrease considerably.

The available data permit to determine the heat flux deposited onto the surface under tokamak disruption and therefore, to estimate a mass of evaporated material. However, there are indications [3] that graphite damage results not solely from atomic vaporization but also from brittle macroscopic destruction and that the eroded carbon is emitted as grains. Investigation of this phenomenon is of great importance because at sufficient heat load the macroscopic erosion leads to greater surface damage and a greater amount of carbon dust than vaporization.

In the present work, the properties of eroded and redeposited graphite targets exposed to intense plasma stream under conditions typical for a hard ITER disruption are studied at the plasma gun facility MK-200 UG in Troitsk.

2. Experimental

The basic scheme of the MK-200 UG facility is shown in Fig. 1. The facility consists of a pulsed plasma gun, a long drift tube and a target chamber. The plasma gun is fed from 1152 μF capacitor bank at an operating voltage of 25 kV. This corresponds to 360 kJ energy stored in the capacitor bank.

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The drift tube consists of a 6.5 m cylindrical part and a conical one with a length of 3 m. The diameter of the cylindrical tube is 30 cm. At the conical section, the tube diameter reduces towards its exit from 30 to 15 cm. A 0.7 T longitudinal magnetic field is generated inside the cylindrical tube. The magnetic field strength rises from 0.7 up to 2.5 T along the conical part.

Samples to be exposed are placed at the end of the drift tube in the target chamber of 30-cm diameter and of 50-cm length. The chamber is filled with a longitudinal magnetic field of 2 T. The parameters of the hydrogen plasma stream at the target position are as follows: power density, $W = 30$–40 MW/cm^2, energy density, $Q = 1.5$ kJ/cm^2, plasma stream diameter, $d =$ 6–8 cm, velocity, $V = (6$–$7) \times 10^7$ cm/s, plasma beta, $\beta = 0.3$, plasma pulse duration, $t = 40$–50 μs. The total energy of the plasma stream is 50 kJ.

POCO, ATJ and MPG-8 graphites manufactured with a surface roughness below 1 μm were employed as target materials. The targets were exposed to normal and inclined plasma impact.

Redeposited graphite layers are obtained at the target surface and at special collectors placed at different distances around the target. Polished plates of graphite, tungsten, silicon and quartz are employed as collectors. The surface structure of irradiated graphite and the thickness of the redeposited layers were analysed by means of optical and electron microscopy, profilometry, microscopic interferometry. The mass of redeposited layers was measured by weighting, while X-ray technique was applied for a phase analysis of redeposited carbon. Deuterium retention in the redeposited carbon layers was studied by thermal desorption spectroscopy. Laser scattering technique was applied for on-line measurement of graphite particles emitted from the irradiated surface.

3. Experimental results

3.1. Erosion rate

Plasma-induced erosion was measured to be similar for POCO, ATJ and MPG-8 graphite samples. The erosion rate is about 0.4 μm/shot at perpendicular plasma impact. Energy consumed for graphite vaporization is around 3 J/cm^2 that corresponds to 0.2% of the plasma stream energy density ($Q = 1.5$ kJ/cm^2). Sufficiently small erosion is explained by effect of target plasma shield. With no shielding effect, the erosion rate would be about 200 μm/shot for the same heat load. In terms of erosion, the reduction factor due to the shielding effect is about 500.

The angular dependence of graphite erosion was studied. Perpendicular (0° tilted) and tilted targets at an angle $\alpha = 30^{\circ}$, 50° and 70° were examined. The maximum erosion rate (0.4 μm/shot) was measured with a perpendicular target. The erosion rate decreases with the target inclination (but less quickly than the plasma heat load $Q_\alpha = Q\cos\alpha$ and becomes 0.22 μm/shot for a 70°-tilted graphite target.

3.2. Erosion products

Fig. 2 shows the surface profile of plasma-irradiated graphite measured with a laser profilometer. The white line shows the averaged magnitude of the erosion. The erosion profile is disturbed by stochastic oscillations with amplitude greater than the averaged erosion. The target was also analysed by means of SEM, and a granular structure on the irradiated surface was found. Typical size of granules is 2–3 μm. Macro- and microscopic surface roughness indicates that graphite erosion occurs with no constant rate on the irradiated surface and that eroded graphite might be emitted as particles.

Laser scattering technique was applied for on-line measurements of graphite particles emitted from the irradiated surface. The diagnostics is capable of detecting graphite particles with a size of $d \geqslant 0.4$ μm. The measurements were performed in front of the target at a distance of 5 mm. No graphite particles were found.

The laser scattering diagnostics was employed also in an experiment with aluminum target. There, aluminum droplets with a diameter $d = 0.3$–3 μm moving with a velocity $v = 1$–10 m/s perpendicular to the target surface were measured.

Graphite erosion products were obtained and analysed at the collectors placed around the target.

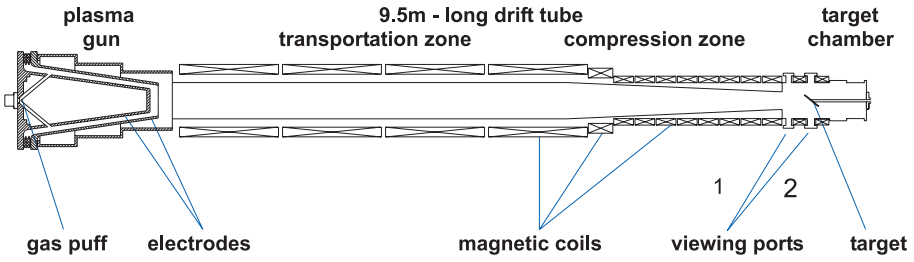

Fig. 1. Basic scheme of the MK-200 UG facility.

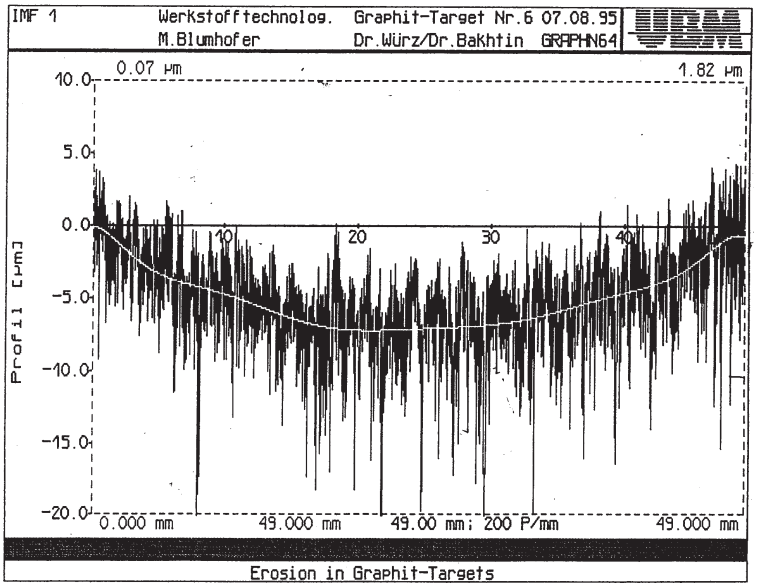

Fig. 2. Erosion profile on a graphite target exposed to 20 perpendicular plasma discharges.

Redeposited graphite produces thin carbon films at the collectors. The films look rather homogeneous without any evidence of micron particles.

Two different assumptions may be drawn from the available data:

1. Brittle destruction is not a true mechanism of graphite erosion for the MK-200 experimental condition.
2. Graphite erosion products are emitted as grains but they are evaporated in the vicinity of the surface.

Let us assume that eroded graphite is emitted as particles of spherical shape with a radius r. Due to the rather small velocity ($v \geqslant 10$ m/s), the particles remain near the surface during the interaction process ($L = vt < 1$ mm, $t = 50$ μs). Particles are evaporated under action of the heat flux $W_s \approx 500$ kW/cm^2 passing through the target plasma shield onto the surface. The evaporation is described by the following equation:

$$4\pi r^2 W_s = -q_v \frac{dV}{dt} = -q_v 4\pi r^2 \frac{dr}{dt},$$

where $q_v = 80$ kJ/cm^3 is the specific vaporization energy. Integration gives a minimal radius of particle, which is not evaporated during the process

$$r_{min} = \frac{W_s}{q_v} t = 3 \text{ μm}.$$

It means that all particles with a diameter smaller than 6 μm will be completely vaporised near the surface and there is no chance to observe such particles at large distances. Therefore, the question on brittle graphite destruction remains open and demands other experimental verifications.

3.3. Redeposited carbon layers

Eroded graphite is detected in the whole volume of the interaction room, at the collectors and at the target surface itself. Eroded graphite appears to be captured as thin films of redeposited carbon. The film thickness is measured to be 0.05–5 μm after 10–30 plasma discharges. Redeposited layers of maximal thickness are formed at graphite target surface.

Phase structures of original graphite and of erosion products were studied by means of X-ray diffractometry. Original graphite shows a hexagonal crystal structure typical of industrial reactor graphite. Redeposited carbon is amorphous at the collectors, i.e., it is soot. At the target surface, redeposited carbon is mainly amorphous indicating an insignificant amount of graphite crystals.

Fig. 3 shows the profile surface for a 20°-tilted target. One can see a layer of redeposited carbon outside the erosion crater. The volume of redeposited carbon is of the same order of magnitude as the volume of eroded carbon. The amount of carbon redeposited on the target surface depends on the angular target position. At a perpendicular target, a volume of redeposited material is negligible but increases with the target inclination. It is explained by different dynamics of eroded material at perpendicular and tilted surfaces [4].

At a perpendicular plasma impact, carbon target plasma expands upward the plasma stream along the

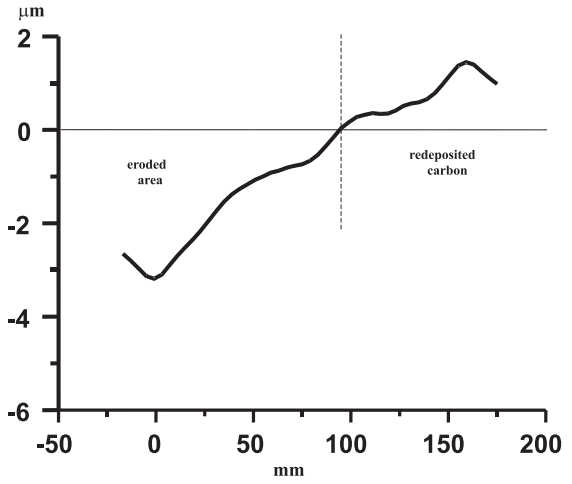

Fig. 3. Surface profile of a 20°-tilted graphite target exposed to 15 plasma discharges (plasma stream direction: left to right; stream axis: $X = 0$.)

magnetic field lines, and transverse motion is basically inhibited. At inclined incidence, a bulk of the target plasma moves down the tilted plate with a rather small velocity. A part of the eroded carbon remains at the surface producing the redeposited carbon layers. Redeposited carbon covers practically the whole tilted surface and seems to mask a real erosion profile.

Properties of redeposited carbon layers depend considerably on the distance to the target. First, the greater the distance the lesser is the layer thickness. Besides, at large distances ($l > 5$–7 cm) the layers are friable and usually they have low adhesion to the collector. Being formed in a plasma discharge, the friable layers can be removed from the collector surface in the next one. Thickness of such layers does not increase with the number of shots.

Close to the target and at the target itself, eroded graphite forms carbon layers baked to the surface. Baked carbon layers have the same hardness as basic graphite. The best layer adhesion is observed at the collectors made of graphite. Layer thickness grows linearly with the number of shots.

The thickness of redeposited carbon layers is found to be limited at the tungsten collector. The maximum thickness is restricted to 1–1.5 μm, and carbon films of greater thickness are destroyed due to flaking probably caused by the different thermal expansion of carbon films and tungsten. Flaking produces large graphite debris. This indicates that carbon dust can be produced not solely due to brittle graphite erosion but also due to destruction of the redeposited carbon layers. Specific weight of the redeposited carbon was measured to be 1.1–1.2 g/cm^3 at the tungsten collector.

3.4. Deuterium retention

Thermal desorption spectroscopy [5] was employed for the measurement of deuterium retention in redeposited carbon layers. The graphite target was exposed to a deuterium plasma stream and POCO graphite and tungsten plates were used as collectors as shown in Fig. 4. The collectors were placed in front of the target (position 1, high temperature region) and behind the target (position 2, low temperature region).

Fig. 5(a) shows the thermal desorption spectra of D_2 and HD molecules from the graphite collector covered by 1-μm redeposited carbon layer. On the other hand, Fig. 5(b) shows the measurements on the same collector but after a mechanical removal of a 30 μm surface layer. The relative analysis of these data indicates that deuterium is accumulated mainly in the redeposited carbon layer and it does not penetrate significantly into the bulk of the graphite collector. The measured deuterium retention is 5×10^{17} D/cm^2, while the deuterium concentration is D/C = 0.1 (10% of atomic concentration).

Analogous measurements were done with the redeposited carbon layer obtained on the tungsten collector (position 2). Concentration of deuterium in carbon film was measured to be above 30%, while deuterium retention is 1.5×10^{18} D/cm^2.

Deuterium concentration was found to be rather small ($D/C \leqslant 2\%$) in the carbon layers obtained in front of the target (position 1). The different deuterium retention in the redeposited carbon produced behind and in front of the target is likely to be explained by the different temperatures of the collectors. In front of the target, the collectors are exposed to intense radiation emitted by carbon target plasma, which causes an evaporation of the collector surface. As known, the D/C ratio is strongly temperature dependent, and decreases to very low values at temperatures above 600°C and saturates at about 0.4 D/C at temperatures lower than 300°C [5]. Behind the target, the temperature is low and deuterium concentration is close to saturation.

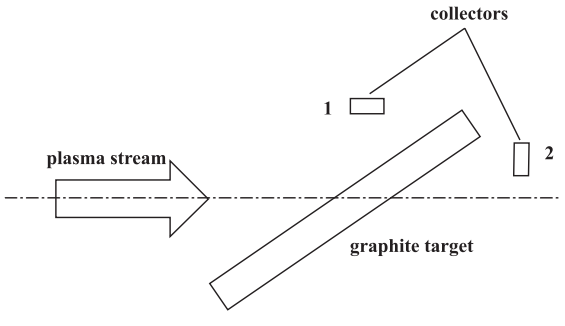

Fig. 4. Position of the eroded carbon collectors.

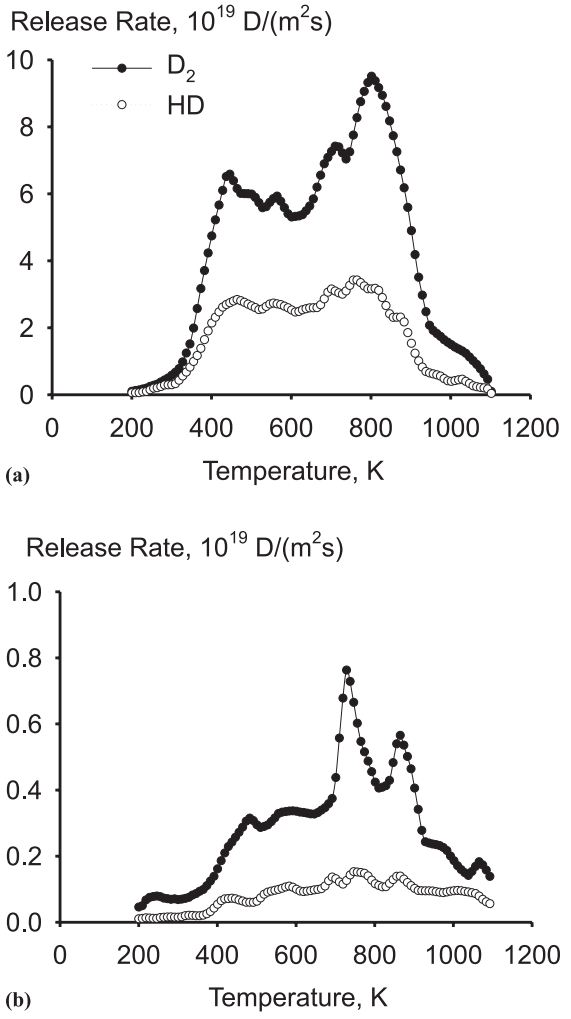

Fig. 5. Thermal desorption spectra of D_2 and HD molecules. Heating rate : 9.8 K/s. (a) graphite collector covered with 1 μm redeposited carbon layer; (b) graphite collector after removal of 30 μm surface layer.

4. Summary

Plasma-induced erosion and graphite erosion products were experimentally investigated under conditions typical for ITER hard disruption. The results are summarized briefly as follows:

- Maximal erosion rate is measured at perpendicular plasma impact. Erosion decreases with sample inclination. Target plasma shield protects effectively the irradiated surface from excessive evaporation. In terms of erosion, the reduction factor due to the shielding effect is about 500.
- Eroded carbon is redeposited back on the irradiated surface, and the amount of redeposited carbon increases with the inclination of the target. Redeposited carbon layers are baked to the surface and have the same hardness of the original graphite.
- Micron graphite particles are not found among the erosion products.
- Eroded graphite is distributed around the whole volume of the interaction room and appears to be captured as thin (0.05–5 μm) redeposited carbon layers.
- The phase structure of redeposited carbon is amorphous, i.e., it is soot.
- The properties of the redeposited carbon layers depend on the collector position. Near the target, the layers show high hardness. Friable carbon layers are formed at large distances.
- Graphite layer flaking producing graphite debris is found at the tungsten collector. Flaking arises when the film thickness becomes larger than 1 μm.
- Redeposited carbon layers accumulate deuterium. Deuterium atomic concentration is measured to be of $D/C \leqslant 2\%$ in the redeposited carbon layer near the exposed target surface and $D/C \leqslant 30\%$ in the layers produced behind the target.

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