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Journal of Nuclear Materials 307–311 (2002) 1364–1368

journal of nuclear materials

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Erosion mechanism and erosion products in carbon-based materials

N. Arkhipov [a], V. Bakhtin [a], V. Barsuk [a], S. Kurkin [a], E. Mironova [a], G. Piazza [b], V. Safronov [a,*], F. Scaffidi-Argentina [b], D. Toporkov [a], S. Vasenin [a], H. Würz [b], A. Zhitlukhin [a]

[a] *Troitsk Institute for Innovation and Fusion Research, 142190 Troitsk, Moscow region, Russia*
[b] *Forschungszentrum Karlsruhe, EURATOM Association, P.O. Box 3640, 76021 Karlsruhe, Germany*

Abstract

Plasma/material interaction was studied in disruption simulation experiments at the plasma gun facility MK-200. Graphite and carbon-fibre composites were exposed to pulsed energetic plasma under heat loads typically expected for disruptions in future tokamaks. Erosion rates, erosion mechanisms and the properties of the eroded carbon have been studied.

1. Introduction

During tokamak plasma disruptions, the divertor plates are exposed to an intense flow of hot plasma. In a future tokamak, the divertor heat flux will be so intense that it can cause severe erosion of plasma facing materials. Erosion limits the lifetime of the divertor components and results in the production of dust, which presents a serious problem for a safety because of its chemical reactivity and, when being tritiated, its radioactivity. The exact amount and properties of the eroded material is critically important for the lifetime and safety analysis of a tokamak-reactor.

In the next-step device ITER-FEAT, the divertor heat loads are estimated to be 10–100 MJ/m^2 for the thermal quench phase (1–10 ms) of disruptions [1]. Such energy densities cannot be achieved in current tokamak machines. Therefore, plasma-induced erosion is investigated by using powerful plasma devices capable to simulate, at least in part, the loading conditions expected for plasma disruption.

Since 1993, the interaction of a hot plasma stream with candidate divertor materials is investigated at the plasma gun facility MK-200 [2] under conditions simulating hard tokamak disruptions. Experimental data are used for the development and validation of appropriate theoretical models. The recently developed 2-dimensional numerical code FOREV-2 [3] quite well reproduces the experimental results thus demonstrating that the physical models used for a description of the plasma/material interaction are adequate.

Experimental and theoretical investigations [4–7] have shown that disruptive heat loads result in a sudden evaporation of a thin surface layer of the irradiated material and produce a cloud of dense vapor plasma. The vapor plasma acts as a thermal shield, stops the plasma stream and protects the surface from the direct action of the hot plasma. The target plasma dissipates the incoming energy flux into photon radiation thereby reducing the heat load to the surface. Due to the vapor shielding effect the erosion by vaporization decreases considerably [8].

Available data permit to determine the heat flux reaching the surface under tokamak disruptions and, therefore, to estimate a mass of evaporated material. However, plasma induced erosion results not solely from atomic vaporization but also from macroscopic

* Corresponding author. Address: Troitsk Institute for Innovation and Fusion Research, 142092 Troitsk, Moscow region, Russia. Tel.: +7-095 334 5240; fax: +7-095 334 5776.
E-mail address: vsafr@rico.ttk.ru (V. Safronov).

0022-3115/02/$ - see front matter
PII: S0022-3115(02)00963-7

processes. In carbon-based materials, erosion products are emitted as carbon grains due to brittle destruction [4,9–13]. Investigation of brittle destruction is of great importance because at adequate heat load the macroscopic erosion leads to greater surface damage and greater amount of carbon dust than the vaporization [14–16]. According to the numerical simulation model described in [14], there are indications that brittle destruction might increase with the number of plasma discharges because of crack propagation into the depth of the sample thus resulting in material pre-damaging.

In the present work, standard reactor graphite MPG-8 and carbon-fibre composites SEP NB31 (pure carbon) and NS31 (silicon doped) have been tested at the MK-200 plasma gun facility under plasma heat fluxes typical for hard tokamak disruption. Erosion rate, erosion mechanisms and properties of the eroded carbon have been studied.

2. Experiment

The experiments were carried out at the MK-200 facility consisting of the two plasma gun devices: MK-200UG and MK-200CUSP. The basic scheme of the MK-200UG is shown in Fig. 1. The facility consists of a pulsed plasma gun, a long drift tube and a target chamber. The plasma gun injects a hydrogen plasma stream into the 9.5 m drift tube, where the plasma stream moves along the magnetic field lines. The plasma stream is magnetized and compressed in a conical section of the drift tube. The samples are placed at the end of the drift tube in the target chamber filled with a longitudinal magnetic field of 2 T. The scheme of the MK-200CUSP machine is very similar to the MK-200UG device. The main difference is the smaller length ($l = 1.2$ m) of the drift tube at the MK-200CUSP, whereas in a short drift tube the plasma stream density and the pressure are greater than in a long drift tube. Table 1 shows the plasma stream parameters measured in both devices at the target position. The MK-200CUSP was applied mainly to study the effect of a high plasma pressure on carbon erosion.

Table 1
Plasma stream parameters

Parameters	MK-200UG	MK-200CUSP
Energy, MJ/m^2	14	15
Pulse duration, μs	40–50	7–12
Diameter, cm	6	5
Ion energy, keV	1.5	1
Beta-value	0.3	1
Pressure, MPa	0.8–1	7–10

Graphite and CFC targets were prepared in the form of rectangular flat plates. The target size was greater than the plasma stream diameter. Targets were exposed to perpendicular and inclined plasma impact. MPG-8 graphite targets were manufactured with a surface roughness below 1 μm in order to allow the use of a mechanical profilometer for the measurement of erosion profiles. The mass loss was measured by weighting the target before and after the irradiation. The erosion of CFC targets was evaluated through the mass loss measurements only. The surface damage was investigated by means of SEM.

Erosion products were collected at special collectors placed at different distances around the target. Eroded carbon particles were collected during 1 or 2 plasma shots. After several exposures a black layer of redeposited carbon arises and black carbon particles cannot be distinguished against the background of the redeposited carbon layer. The collected particles were analysed using an optical microscope provided with a CCD camera, and the size of the particles was measured. Erosion products were studied also by X-ray diffractometry in order to determine the percentage of the crystalline graphite particles in the erosion products.

3. Experimental results

3.1. Graphite

Table 2 shows the erosion of MPG-8 graphite measured in the MK-200UG experiment. Perpendicular (0°)

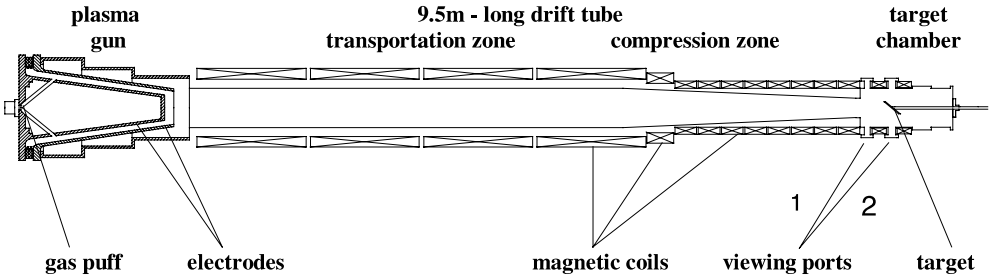

Fig. 1. Basic scheme of the MK-200UG machine.

Table 2
Erosion of MPG-8 graphite

Angle (°)	Erosion (μm/shot)
0	0.4
30	0.4
50	0.34
70	0.22

and tilted targets with tilting angles of 30°, 50°, 70° were used. The erosion was measured after 10–15 plasma exposures and the erosion per shot was evaluated. It is 0.4 μm/shot for perpendicular plasma impact. This accounts for an energy consumed for graphite vaporization of around $Q_v = 30$ kJ/m^2 corresponding to 0.2% of the plasma stream energy ($Q = 15$ MJ/m^2). This quite small erosion is explained by the shielding effect. With no shielding effect, when the plasma stream energy is consumed completely for graphite heating and vaporization, the erosion rate would be about 200 μm/shot. In terms of erosion, the reduction factor due to the shielding effect is about 500 [4].

Maximum erosion was measured at the perpendicular target (Table 2). The erosion decreases with the target inclination (but less quickly than the plasma heat load $Q_\alpha = Q\cos\alpha$) and becomes 0.22 μm/shot at the 70° tilted graphite. These measurements were done for 'large' targets, which overlap fully the plasma stream. At 'small' targets the erosion rate increases with sample inclination [2]. The incident plasma stream blows away the target plasma from the 'small' tilted surface causing a loss of vaporized material and a reduction of the shielding effect.

The eroded products are emitted as carbon vapor and carbon particles. The carbon vapor redeposits at nearby components and produces redeposited carbon layers. As shown in [17] redeposited carbon has an amorphous structure. On the other hand, the eroded particles maintain the MPG-8 graphite original phase structure with hexagonal crystal structure.

The erosion products collected near the exposed graphite target were analyzed by X-ray diffractometry. About 5–10% of the collected erosion products were crystalline particles, and as these particles are formed due to brittle destruction, one could conclude that brittle destruction contributes only a little (5–10%) to the net erosion of graphite. However, the real contribution of macroscopic erosion might be greater than 5–10% because a fraction of the eroded particles is evaporated in the plasma shield near the target surface. In fact, because of their rather small velocity $v \leqslant 10$ m/s [18], the eroded particles remain close to the surface ($L = vt < 1$ mm) during the interaction process ($t = 50$ μs) and they can be evaporated under the action of the effective heat flux which reaches the exposed surface through the shielding layer and which is only about $W_s = 6$ GW/m^2.

The evaporation of spherical particles 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 $q_v = 100$ kJ/cm^3 is the specific vaporization energy [19], V the particle volume and r the particle radius. Integration gives a minimum particle radius, above which the particles are not completely evaporated during the process:

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

It means that the particles with a diameter smaller than 6 μm will be completely vaporized if they are formed at the beginning of the plasma exposure. Therefore only the particles formed later and the particles of greater size can be detected in the collected erosion products. The question on the contribution of brittle destruction to the net erosion remains open and demands further experimental investigations [16].

Fig. 2 shows the size distribution of the carbon particles. The particle size was evaluated as $d = (4S/\pi)^{1/2}$, with S being the area of the particle projection on a plane of the collector surface. The distribution is peaked at $d = 1$–3 μm. Almost 80% of the collected particles are in this range. Large particles are present also but their percentage decreases rapidly with particle size. The measured size of eroded particles agrees well with the size of the granules observed by SEM at the irradiated target.

The size distribution in Fig. 2 was obtained after analysis of 7500 carbon particles. Such number of particles were collected during one plasma shot at the ceramic plate of $S_c = 0.25$ cm^2 area, which was placed at a distance of $R = 8$ cm from the target centre. The volume

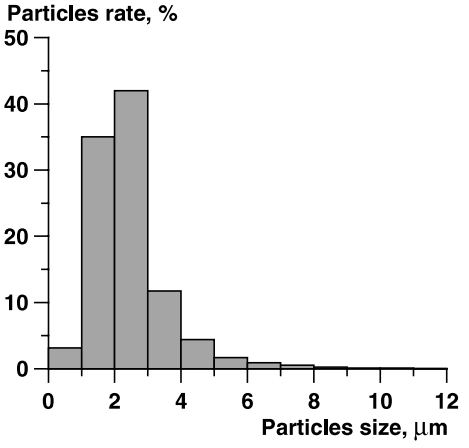

Fig. 2. Size distribution of carbon particles emitted from MPG-8 graphite in the MK-200UG experiment.

of the collected particles is about $V = N(\pi/6d^3) \approx 10^5$ μm^3. Under the assumption that the emission of the particles is isotropic, the total volume of emitted particles $V_t = V(2\pi R^2)/S_c$ is estimated as 1.5×10^8 μm^3. The volume of eroded graphite is about 2×10^9 μm^3/shot. Thus the carbon particles are responsible for about 10% of the total amount of eroded material which agrees well with the measured crystalline fraction in the erosion products.

3.2. Carbon fiber composites

Carbon fiber composites SEP NB31 and NS31 were tested at the MK-200UG machine (impact plasma pressure $P = 1$ MPa) and at the MK-200CUSP ($P = 10$ MPa). Each CFC sample was exposed to 40 plasma shots: 30 shots at $P = 1$ MPa and 10 shots at $P = 10$ MPa. The amount of eroded material was quantified by weighing the sample before and after plasma exposure. The mass loss was measured after each set of 10 shots, then the magnitude of Δm was evaluated for one shot. For comparison, the mass loss of graphite was also measured. The obtained results are summarized in Table 3. It should be noted that a mass loss of $\Delta m = 1$ mg/shot corresponds to an erosion of about 0.1 μm/shot.

Experiments with different plasma pressures were performed to study the effect of the external pressure on the onset of brittle destruction and on the net erosion. The obtained data (Table 3) indicate that the net erosion has in both facilities the same order of magnitude. However the pulse duration in both facilities is quite different. This indicates a certain influence of the plasma pressure on the net erosion and thus on brittle destruction.

Fig. 3(a) and (b) show the size distributions of carbon particles eroded from SEP NB31. The distributions are the same for SEP NS31. At a plasma pressure of $P = 1$ MPa, the size distribution is peaked at $d = 1$–2 μm (Fig. 3(a)). With increasing plasma pressure the size of the particles increases (Fig. 3(b)) and a greater number of particles is obtained at the collector. High pressure seems to intensify the brittle destruction of CFC, however it does not result in an increase of the net erosion. As shown in [13] an additional surface screening arises due to particle evaporation.

Table 3
Mass loss of carbon based materials

Material	Facility	Δm (mg/shot)
SEP NB31	MK-200UG	1.0
SEP NS31	MK-200UG	1.3
MPG-8	MK-200UG	4
SEP NB31	MK-200CUSP	1.2
SEP NS31	MK-200CUSP	1.3
MPG-8	MK-200CUSP	2.5

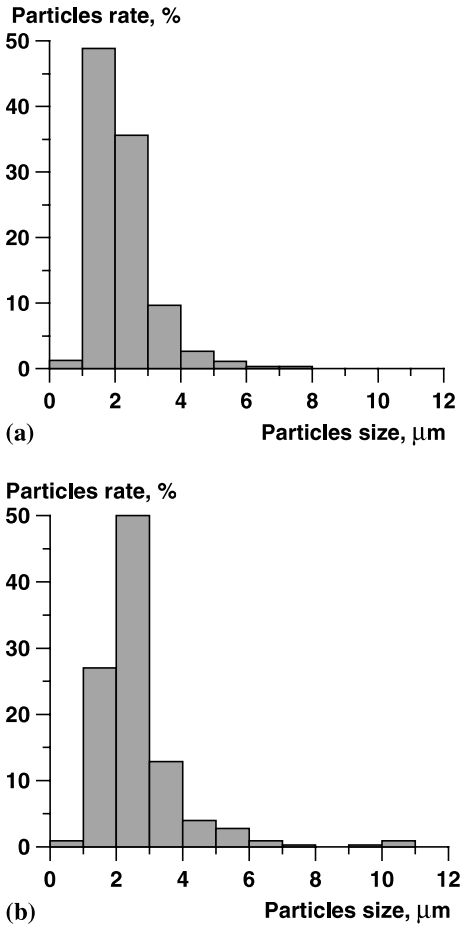

Fig. 3. Size distribution of carbon particles emitted from SEP NB31: (a) MK-200UG, $P = 1$ MPa; (b) MK-200CUSP, $P = 10$ MPa.

Surface damages were analysed by means of SEM after each set of 10 shots. Only microcracks (Fig. 4(b)) were observed at the CFC surface after the first 10 shots. After 20–30 shots, large holes were formed with a typical size of 100–200 μm (Fig. 4(c)). There are also holes of 1 mm size but the amount of such holes is very small. The holes arise because of crack formation resulting in macroscopic destruction. Fig. 4(d) shows a macroparticle, which still remains at the surface but is separated by cracks from the target body.The holes appear after 20–30 shots and their number increases with the number of exposures. However the mass loss remains about 1 mg/shot thus indicating that the emission of macroparticles contributes only little to the resultant mass loss. The mass of 100–200 μm particle is 10^{-3} to 10^{-2} mg. A contribution of the macroparticles would be about 1 mg/shot if 100–1000 particles were emitted in one shot.

In the present experiment, erosion of the CFC targets was measured to be lower than graphite erosion

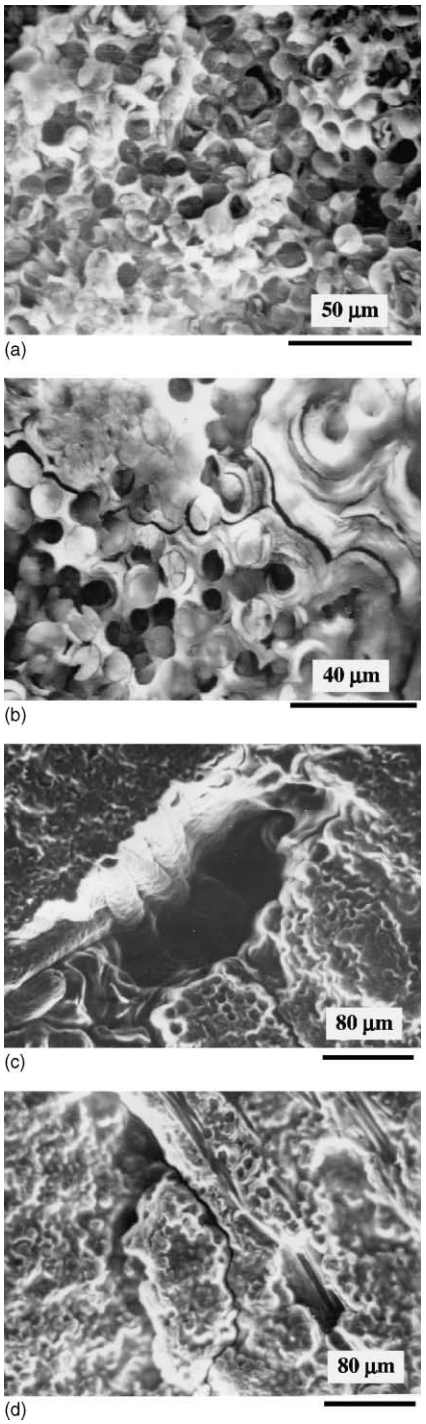

Fig. 4. SEM images of SEP NB31 before and after plasma irradiation at the MK-200UG: (a) initial state; (b) after 10 shots; (c,d) after 30 shots.

(Table 3). However it is too early to conclude that the CFC target withstands the disruption heat loads better than graphite because the CFC targets were tested in 40 plasma shots only. Formation of cracks and holes might cause a degradation of the CFC properties and an increase of erosion. Experimental investigations should be continued.

4. Summary

Graphite MPG-8 and carbon-fibre composites SEP NB31 and NS31 have been tested in disruption simulation experiments at the MK-200 plasma gun facility. The obtained results are summarized briefly as following:

- Plasma induced erosion of carbon based materials decreases considerably due to the shielding effect. In terms of erosion, the reduction factor is about 500 for graphite and above 1000 for CFC.
- Erosion of carbon based materials results from evaporation and brittle destruction. The erosion products are emitted as carbon vapor and as carbon particles. In the collected erosion products the fraction of carbon particles is about 10% of the total.
- The size distribution of the eroded carbon particles is peaked at 1–3 μm. With increasing plasma pressure the particle size distribution shifts to larger particles.
- Pulsed energetic plasma causes formation of cracks and 100–200 μm holes in the exposed CFC surface. The holes arise because of brittle destruction and emission of material debris.

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