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Erosion characteristics of neutron-irradiated carbon-based materials under simulated disruption heat loads

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Abstract

This paper presents disruption simulation experiments on neutron-irradiated carbon-based materials to investigate the erosion characteristics of irradiated materials. Uni-directional (1D) and 2D carbon fiber reinforced carbon composites (CFCs), which are one of the promising materials for the plasma facing components of the fusion experimental reactors, were selected as a test material. These samples were irradiated by neutrons with a total neutron fluence of $3.2–5.6 \times 10^{24}$ n/m^2, which corresponds to 0.3–0.5 dpa, at an irradiation temperature of 280–320°C. After the neutron irradiation, disruption simulation experiments were carried out at the electron beam facility in the hot-cell under a heat load of 20 MJ/m^2, which simulates the ITER disruption conditions. As a result, the weight losses of neutron-irradiated 1D and 2D CFCs increase as the neutron fluence increases. The maximum erosion depth does not change with the neutron fluence. The surface erosion profile is much broader with increasing neutron fluence. It can be seen that the increase in weight loss was caused by the broadened erosion profile.

1. Introduction

Plasma disruption is one of the off-normal events in tokamak devices, in which the plasma energy is deposited on the surface of plasma facing materials (PFMs) within a few milliseconds. This energy deposition causes severe erosion and damage of the materials. Carbon fiber reinforced carbon composites (CFCs) are candidate materials for the plasma facing components of the next fusion devices because they do not melt under disruptions and might have higher erosion lifetime in comparison with other possible armor materials such as Be and W [1]. However, PFMs of the next generation fusion devices, i.e., the International Thermonuclear Experimental Reactor (ITER) will be exposed to intense neutron fluxes [2]. The disruption erosion of CFCs is expected to increase because of the decrease in thermal conductivity of CFCs as a result of neutron irradiation [3]. Although a lot of disruption simulation experiments for the un-irradiated specimens have been reported [4–6], no erosion data have been presented for neutron-irradiated materials. To investigate the erosion characteristics of neutron-irradiated PFMs, disruption simulation experiments were performed.

2. Experimental procedure

The electron beam facility, Oarai Hot-cell Beam Irradiation System (OHBIS) was applied for disruption simulation experiments. Major performance of OHBIS is shown in Table 1 [7]. Before the disruption simulation experiment, the maximum heat flux and their profile of the electron beam were experimentally measured by a graphite calorimeter [8]. Fig. 1 shows typical beam profiles as a function of beam current. In the OHBIS facility, the electron beam produced at the gun is focused by the

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Table 1
Major performance of OHBIS

Max power density	$\leqslant 2.5$ GW/m^{2}[a]
Beam power	$\leqslant 50$ kW
Beam potential	30 kV
Beam current	$\leqslant 1.7$ A
Beam scanning	Sin wave $\leqslant 1$ kHz, ± 150 mm in X, Y
Exposure time	$\geqslant 0.1$ ms
Moving time	$\geqslant 0.1$ ms

[a] Calculated value at $\phi 5$ mm in dia. of E.B.

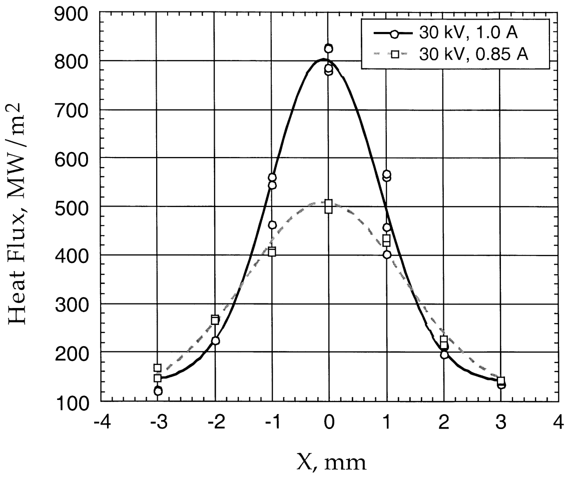

Fig. 1. Typical beam profiles of OHBIS.

focusing lens system. Since in the focusing lens system it is difficult to control every shot, two types of beam profile are applied, although 0.85 A condition was unfocused, in these experiments as shown in Fig. 1.

Uni-directional CFC (MFC-1) and 2D CFC (CX-2002U), whose thermal conductivity are shown in Table 2 were selected as test samples. The dimension of the specimens was $11.5^{l} \times 11^{w} \times 7.5^{h}$ mm. These samples were irradiated by neutrons in Japan Materials Testing Reactor (JMTR) with the total neutron fluence ($E > 1$ MeV) of 3.2–5.6×10^{24} n/m^2, which corresponds to 0.3–0.5 dpa, at an irradiation temperature of 280–320°C. After the neutron irradiation, disruption simulation experiments were carried out at OHBIS under the heat load condition of 20 MJ/m^2 (800 MW/m^2, 25 ms and 500 MW/m^2, 40 ms), which simulates the ITER disruption conditions (20–100 MJ/m^2).

Table 2
Thermal conductivity of test specimens

CFC material	Thermal conductivity (W/m/K) at RT		
	X	Y	Z
MFC-1 (1D)	640	25	25
CX-2002U (2D)	380	320	215
MFC-1 (0.70 dpa)	130	–	–
CX-2002U (0.42–0.47 dpa)	68	–	52

Weight loss of each specimen was measured by an electronic micro-balance before and after the disruption simulation experiments. Eroded surface profile of each specimen was also measured by a laser micro-profilometer to estimate the erosion depth.

3. Experimental results

Fig. 2 shows weight losses of MFC-1 and CX-2002U as a function of neutron fluence for different heat fluxes. The weight losses of both CFCs increase as the neutron fluence increases. The weight loss of the 0.46 dpa specimen is about twice larger than those of the un-irradiated materials. It is considered that the increase of the weight losses was caused by the decrease of the thermal conductivity of CFCs due to the neutron irradiation. Fig. 3 shows the typical eroded surface profile along the center line of the heated area of the MFC-1 and CX-2002U. The maximum erosion depth does not change with the neutron fluence. The surface erosion profile is much broader with the increase of the neutron fluence. It can be seen that the increase of the weight loss was caused by the broadened erosion profile. For the neutron-irradiated specimens, however, 15–20% of decrease of the beam current from 10 to 25 ms was observed during the beam irradiation. To confirm the influence of the decrease of the beam current, numerical analyses were performed.

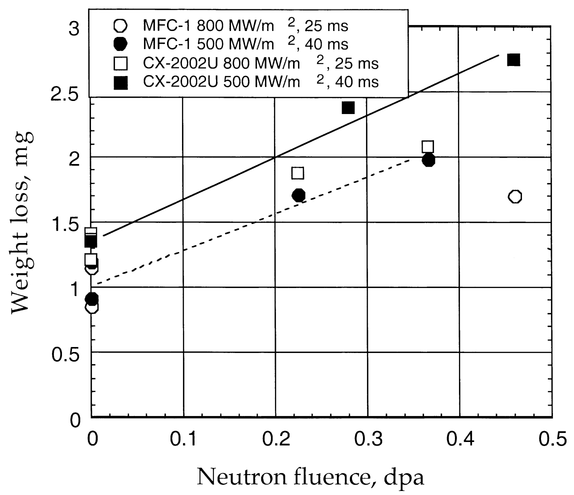

Fig. 2. Weight losses of MFC-1 and CX-2002U as a function of neutron fluence.

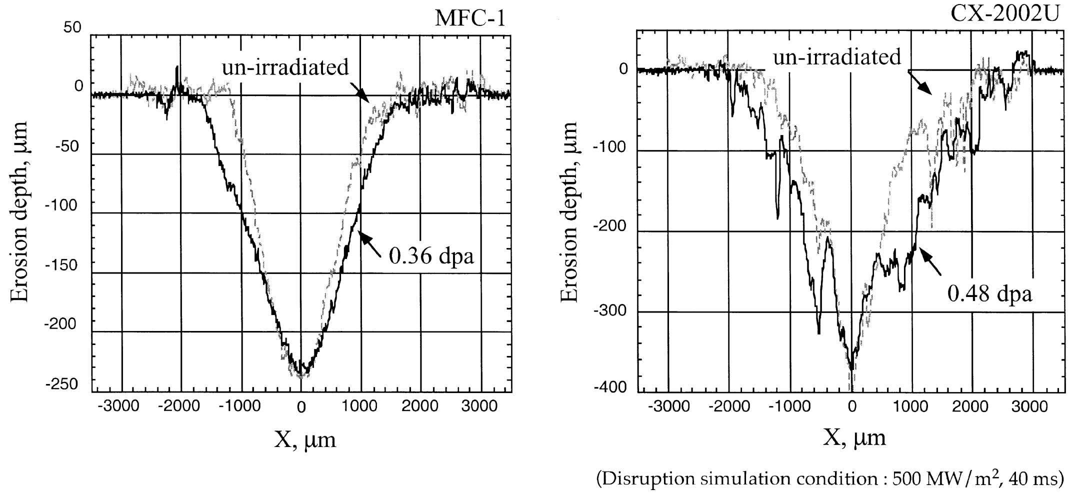

Fig. 3. Typical erosion profiles of MFC-1 and CX-2002U.

4. Discussions

In the previous section, we indicated that the increase of the weight losses is caused by the decrease of the thermal conductivity of the CFCs due to the neutron irradiation. A large erosion volume was produced for the neutron-irradiated specimens because of the decrease of the thermal conductivity. In the experiments, 15–20% of decrease of the incident electron beam current for the neutron-irradiated specimens was observed. This was found only for the neutron-irradiated specimens during the beam irradiation from 10 to 25 ms in case of 25 ms irradiation and from 20 to 40 ms in case of 40 ms irradiation, respectively. It was considered that the incident electron beam was reduced by the emitted particles from the surface. This might cause the decrease of the actual heat fluxes induced to the neutron-irradiated specimens.

The experimental data were analyzed using two-dimensional thermal analysis code [9] which takes account of evaporation process. In the analysis, effects of vapor shielding and particle emission were not considered to simplify the analysis. Major thermal properties of MFC-1 and CX-2002U are summarized in Table 3 [10]. Mass density was assumed to be constant, i.e., 1960 kg/m^3 for MFC-1 and 1680 kg/m^3 for CX-2002U, respectively. The thermal conductivity and the heat capacity of the un-irradiated specimens were assumed to be as a function of temperature as shown in Table 3. Since few thermal properties of the neutron-irradiated CFC materials have been measured, thermal conductivity of the neutron-irradiated CFCs was assumed to be the constant values of 130 W/m/K for MFC-1 and 68 W/m/K for CX-2002U, respectively. In the thermal analyses for the neutron-irradiated specimens, the decrease of the heat flux due to the decrease of the beam current was also taken into account.

Fig. 4 shows the comparison of the eroded surface profiles of MFC-1 between the experimental and the numerical results with a heat load of 800 MW/m^2 for 25 ms. A large difference of the erosion depth between experimental and numerical results was obtained. It was attributed to the particle emission, which was not considered in the analyses. It was confirmed by the SEM observations that the fibers and matrix were lost from

Table 3
Typical thermal properities on MFC-1 and CX-2002U

Mass density (kg/m^3)	MFC-1 (uni-directional CFC) 1960		CX-2002U (two-directional CFC) 1680	
	Thermal cond. (W/m/k)	Specific heat (J/kg/K)	Thermal cond. (W/m/k)	Specific heat (J/kg/K)
At 300 K	640/25/25	720	381.1/215.0	718
At 500 K	439	–	254.2/150.0	1267
At 700 K	373	1480 (673 K)	192.5/116.7	1555
At 900 K	320	–	152.5/93.3	1717
At 1200 K	273	1830 (1730 K)	–	–
After neutron irradiation	130 (0.70 dpa, 1065 K)		68/52 (0.42–0.47 dpa)	

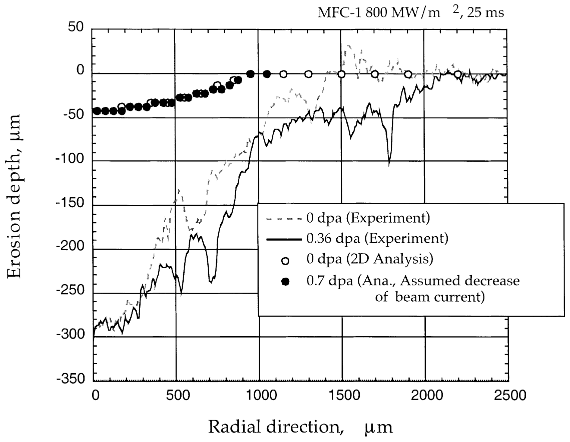

Fig. 4. Comparison of eroded surface profiles of MFC-1 between the experimental result and the two-dimensional analysis.

the heated region not only by sublimation but also by particle emission. The maximum erosion depth obtained from the numerical analysis does not change with the neutron fluence as shown in Fig. 4, which has the same tendency as the experimental result. This is considered to be caused by the decrease of the actual heat flux during the beam irradiation due to large amount of the emitted particles from the neutron-irradiated CFCs in the present experiments. To investigate the detailed erosion characteristics of neutron-irradiated CFC materials, further experiments simulating a plasma disruption should be performed at higher heat fluxes for short pulse length to sustain the stationary heat flux.

5. Conclusion

In this study, the first disruption simulation experiments on the neutron-irradiated carbon-based materials were performed in the OHBIS facility. The effects of the neutron irradiation on the erosion behavior of 1D and 2D CFCs exposed to the simulated disruption heat loads of 20 MJ/m^2 were evaluated. The following results were obtained:

1. Weight losses of neutron-irradiated 1D and 2D CFCs increase as the neutron fluence increases. The weight loss of the 0.46 dpa specimen is about twice larger than those of the un-irradiated materials.
2. The maximum erosion depth does not change with the neutron fluence in the present experiments. The surface erosion profile is much broader with the increase of the neutron fluence. It was found that the increase of the weight loss is caused by the broadened erosion profile in the present experiments.
3. For the neutron-irradiated specimens, decrease of the beam current was observed during the beam irradiation. It was considered that the actual heat fluxes induced to the neutron-irradiated specimens were reduced by large amount of the emitted particles due to the decrease of the thermal conductivity of the neutron-irradiated CFCs. The thermal analyses for the test specimens were performed to clarify the erosion depth. It is found that maximum erosion depth of the experimental results is six times larger than that of the numerical results due to macroscopic particle emission. The fact, that the erosion depth of the neutron-irradiated specimens was almost the same as that of the un-irradiated specimens, can be explained by taking the decrease of the heat flux into account in the thermal analyses.

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