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Estimation of carbon fibre composites as ITER divertor armour

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Abstract

Exposure of the carbon fibre composites (CFC) NB31 and NS31 by multiple plasma pulses has been performed at the plasma guns MK-200UG and QSPA. Numerical simulation for the same CFCs under ITER type I ELM typical heat load has been carried out using the code PEGASUS-3D. Comparative analysis of the numerical and experimental results allowed understanding the erosion mechanism of CFC based on the simulation results. A modification of CFC structure has been proposed in order to decrease the armour erosion rate.

1. Introduction

Carbon fibre composites (CFC) of NB31 and NS31 grades developed for the divertor armour of the future tokamak ITER have shown a high thermal conductivity and a low erosion rate appropriate for the tokamak stationary regimes with characteristic temperatures of 1000–1500 K [1]. However, for the expected slow transient loads of 20 MW/m^2 the experiments on electron beam facilities demonstrated high erosion rates by brittle destruction of NB31 in the temperature range of 3000–3500 K [2]. It is worthwhile to note that at such temperatures, brittle destruction erosion of fine grain graphite armour is much smaller [3].

Numerical simulations for NB31 using the Pegasus-3D code have revealed that the high erosion rate of NB31 is due to the new erosion mechanism due to local overheating [4]. The local overheating erosion mechanism (LOEM) realizes due to the complex structure of CFC, which consists of carbon matrix and carbon fibre reinforcement. Main component of the reinforcement, the pitch fibres, perpendicular to the surface, provides high heat conductivity of CFC. They are woven and needled by the PAN fibres arranged parallel to the surface. A large difference of fibre and matrix coefficients of thermal expansion is essential for LOEM. Enhancement of erosion in LOEM is due to the preferential cracking on the interfaces between fibres and matrix followed by thermal isolation of the PAN fibres from the matrix.

In this work further investigation of CFC erosion under repetitive pulsed heat load simulating type I ELMs in ITER has been performed both numerically and experimentally. Experimental investigations have been done at the plasma gun facilities MK-200UG and QSPA, in which the CFC samples were exposed to hot hydrogen plasma streams. The experimental conditions and the results are described in Section 2. Corresponding numerical simulation has been done using the code Pegasus-3D. The numerical results are described in Section 3. Discussion in Section 4 for the obtained results allows propose improvements of the CFC structure in order to decrease the erosion rate at ITER off normal event conditions.

2. Simulation of CFC erosion with plasma guns

The heat loads with energy density of 1–3 MJ/m^2, during 0.1–0.5 ms in external magnetic field of 6T typical

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for ITER ELMs are not achievable at the existing plasma facilities. Therefore for estimation of divertor armour erosion it is important to use the facilities with the parameters closest possible to the ITER ELM ones. These parameters are realized at the plasma guns MK-200UG [5] and QSPA [6].

In the present work, CFC NS31 and NB31 have been tested at these plasma gun facilities. The CFC samples were prepared in the form of rectangular flat plates of a size greater than the plasma stream diameter. At MK-200UG the targets were irradiated by magnetized hydrogen plasma streams of the diameter $d = 6$ cm with energy density Q of 10–15 MJ/m^2 and pulse duration $t = 40$–50 μs propagating along the magnetic field B of 2 T. At QSPA, the samples were tested by the plasma streams with Q of 10 MJ/m^2, $d = 4$ cm, $t = 500$ μs and $B = 0$. At both facilities, the targets were exposed to perpendicular plasma impacts with the total number of plasma shots $N = 200$. Despite the fact that the plasma stream loads are several times larger than it is expected for ITER ELMs the heat flux at the target surface is closer to the ELM conditions due to the vapour shield effect [7]. The amount of the eroded material was evaluated by weighting the target before and after plasma irradiation. Erosion profile was studied by using a mechanical profilometer. Surface damage was analysed by means of SEM. Erosion products were collected at special collectors placed at different distances around the target, and the sizes of emitted carbon particles were measured.

The measurements have shown that CFC erosion is rather small and limited to a few microns per shot, which is attributed to the shielding. The erosion occurs mainly due to brittle destruction and the erosion products are emitted as carbon particles. According to the previous measurements, about 80% of the collected particles have sizes of 1–3 μm [8]. There are also large particles of sizes of 50–150 μm. Emission of large carbon debris results in formation of open cavities at the CFC surface. The cavities are formed mainly at the boundaries between PAN and pitch fibre bunches. With increase of number of plasma exposures, the cavities overlapped producing micro-channels along the boundaries of the fibre bunches.

Erosion takes place with a varying rate resulting in considerable roughness of the CFC target surface: the PAN fibres erode much larger than the pitch fibres. Fig. 1 demonstrates the profile of exposed target surface, its wavy structure formed by the valleys at the positions of the PAN fibres and by the ridges at the position of the pitch fibres. The erosion difference results from the different erosion mechanisms of the fibres. The PAN fibres are damaged mainly due to brittle destruction while the pitch fibres are eroded only due to vaporization, as is seen from Fig. 2 that demonstrates absence of brittle destruction of the pitch fibres.

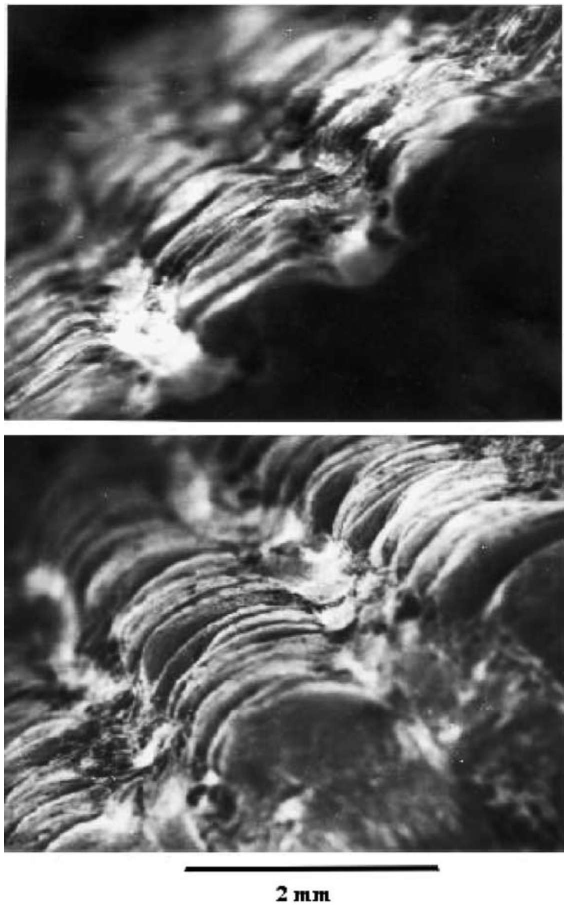

Fig. 1. NS31 surface after 50 plasma shots (upper panel) and after 150 shots (lower panel) at the QSPA facility. Erosion of the PAN fibres parallel to the surface forms the 'valleys', and the pitch fibres are outcropped perpendicularly as the ridges.

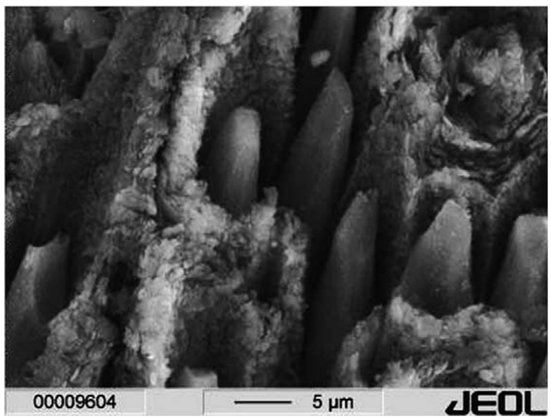

Fig. 2. Erosion of the pitch fibres perpendicular to the sample surface after 150 shots attributed to vaporization is demonstrated. The erosion value is much smaller than that of the PAN fibres.

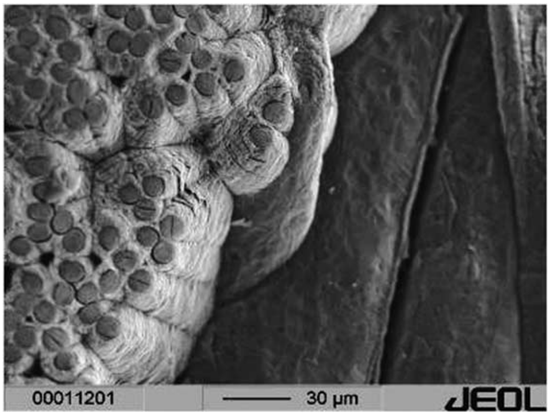

Fig. 3. CFC (NS31) surface after 50 plasma shots at QSPA. Shown is the boundary between PAN and pitch tows. The pitch fibres erosion is negligible. The erosion in PAN fibres region is considerably larger and the surface forms a valley.

During first 50–70 plasma shots, the measured mass loss ($\Delta m = 15$–20 mg/shot) is determined basically by erosion of the PAN fibres. The pitch fibres are damaged only a little (Fig. 3) and their contribution to the net erosion seems rather small. After 70–100 shots, when the longitudinal fibres are eroded at the depth about 0.5 mm, erosion of the pitch fibres grows notably (Fig. 2). During 200 plasma shots the mass loss increases with a number of plasma exposures up to $\Delta m = 40$ mg/shot.

3. Numerical simulation of the CFC erosion during ELM

Because of considerable difference of the ELM simulation conditions in the MK-200UG and QSPA plasma guns from ITER impact the results of the experimentally determined erosion mechanism should be extrapolated on ITER ELM conditions. For this purpose numerical simulation using the code PEGASUS-3D has been performed.

Calculation of CFC erosion under ITER ELM heating by PEGASUS-3D implies definition of the numerical sample simulating the required CFC structure, definition of heating conditions and then calculation of heat transport, thermostress and cracking in the sample. The numerical sample is a part of a cubic array of $200 \times 200 \times 200$ cubic cells. The coordinates origin is in one of the cubic array vertices. The sample is 'cut' from the array by two planes, perpendicular to the main diagonal going from the coordinates origin, see Fig. 4. Such inclined orientation of the numerical sample is caused by necessity to eliminate the influence of cubical structure on the calculation results. Heated is the face of the sample closest to the coordinates origin. The sample has a structure from fibres and matrix arranged similarly to the simulated CFC structure. Similarity of the NB31 fibre structure and the numerical sample is seen from Figs. 3 and 4.

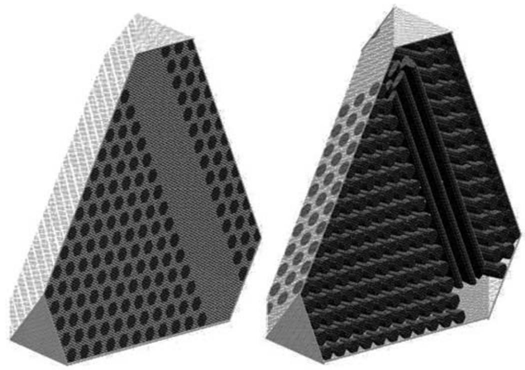

Fig. 4. Numerical sample for CFC NB31 erosion simulation. Heated surface with outcropping pitch fibres on the left and fibre structure with removed matrix on the right are shown.

Previous numeric simulation of the CFC erosion [4] has revealed the peculiarities of the erosion mechanism under long lasting (1–10 s) thermal heat loads, typical of the ITER vertical displacement events. At such conditions a considerable erosion rate has been obtained in the places where the PAN fibres are situated. Expecting the same behaviour for the ELM conditions, the numerical sample has been chosen to represent both surface regions of the NB31 CFC, with PAN and pitch fibres. The region in Fig. 4 with the pitch fibres is in lower left part of the sample and the region with the PAN fibres situated at a depth of few microns under the sample surface is going from upper right to down right corner of the sample. The carbon fibres consist of the cubic cells with two anisotropy axes directed in axial and radial directions of the fibre. The matrix is simulated by small grains of a mean size of ~ 2.5 μm, having random shapes with the anisotropy axes directed randomly for different grains. More details one can find in [4].

Heating of the carbon armour by heat loads typical of the ITER ELMs has been investigated in [9]. The result of the simulation that has been done there allows definition of the following heating scenario. From the start of ELM the sample surface is heated by a constant heat flux till the time, when the surface temperature reaches the carbon sublimation temperature $T_s = 4000$ K. Then, vaporization of the carbon produces the vapour shield. Shielding of the armour surface is a self-adjusted process, which maintains the surface temperature very close to the sublimation temperature. For instance, if the surface temperature T drops slightly less than T_s then vaporization rate is decreasing and corresponding shielding efficiency decrease causes an additional heating, which recovers $T = T_s$ and vice versa, small increase of T is recovered due to corresponding increase of the shield. The calculations showed that the surface temperature oscillations around T_s are small and the boundary condition $T = T_s$ is accurate enough for the heating process inside the target after the vaporization start. The vaporization erosion during ELM is much less than 1 μm. This allows neglecting the vaporization erosion in the simulation of CFC damage despite the fact that the vapour shielding is taken into account.

The results of the simulation are shown in Fig. 5. Most important fact is that under ITER ELM heating the CFC erosion is qualitatively the same as it has been observed in experiments on the plasma guns. Erosion of the PAN fibres, seen as a valley along the left side of the sample in Fig. 5 is much larger than the erosion in the pitch fibres region at the right side of the sample. Besides, erosion of the PAN fibres 'undermines' the matrix between the pitch fibres, stripping them at the boundary between the two regions. As it was found in experiments with NB31 the pitch fibres are eroded mainly by vaporization (Fig. 2). Vaporization is not taken into account in the numerical calculation, so the undamaged pitch fibres stripped of a matrix material are seen at the PAN–pitch boundary in Fig. 5.

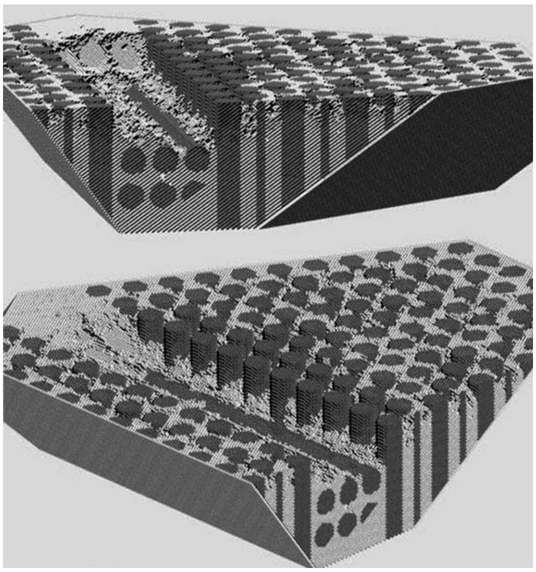

Fig. 5. Calculated pattern for CFC NB31 erosion under ITER ELMs action. Upper and lower panels show the same cross section of the erosion valley. The valley is from erosion of three PAN fibres parallel to the sample surface and of the matrix surrounding them. Preferential erosion of the CFC at the site with PAN fibres and undermining of neighbouring pitch fibres (perpendicular to the surface) is seen. Erosion of the pitch fibres is negligible.

4. Conclusions

Erosion of the NB31 CFC under ITER relevant heat loads has been investigated experimentally and numerically. Because the plasma gun incoming heat loads were 3–10 times larger and time duration either the same or 2–10 times shorter than it would be expected for the ITER ELMs the numerical simulation of CFC behaviour using PEGASUS-3D is necessary in order to extrapolate the experimental results on the ITER ELM conditions.

Both experimental and numerical simulations resulted in the same erosion pattern for the NB31 CFC. The main features of the erosion mechanism are as follows. The erosion starts at the regions with the PAN fibres, which are parallel to the surface. The erosion rate of the PAN fibres is always much higher than that of the pitch fibres, which are perpendicular to the surface. Erosion of the pitch fibres occurs due to vaporization. The 'valleys' along the PAN fibres are 'undermining' from sides the pitch fibres regions inducing additional pitch fibres erosion, see Figs. 3 and 5.

From the results of the simulations done in this paper and in [4] the conclusion is follows that for a significant improvement of the CFC erosion strength at the ITER off normal events (ELMs, VDEs and disruptions) the structure of the CFC should have as less fibres parallel to the armour surface (e.g. weaving and needling fibres) as possible. The best way would be to have one-dimensional CFC with the fibres perpendicular to the surface only. Simulation of erosion strength for a fully one-dimensional fibre structure is not yet done, but from the comparison of the erosion rate of NB31 in the PAN and pitch regions it follows that the erosion rate of a 1D CFC may be about 5 times or even more less than that of NB31.

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