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Fuel removal from bumper limiter tiles by using a pulsed excimer laser

B. Emmoth [a,*], S. Khartsev [a], A. Pisarev [b], A. Grishin [a], U. Karlsson [a], A. Litnovsky [c], M. Rubel [d], P. Wienhold [c]

[a] Department of Microelectronics and Information Technology, Royal Institute of Technology, Association EURATOM-VR, Electrum 229, S-164 40 Kista, Sweden

[b] Moscow Engineering and Physics Institute, Moscow 115409, Russia

[c] Institut für Plasmaphysik, Forschungszentrum Julich, D-52425 Jülich, Germany

[d] Alfvén Laboratory, Royal Institute of Technology, Association EURATOM-VR, S-100 44 Stockholm, Sweden

Abstract

Samples of a limiter tile from the TEXTOR tokamak were investigated by scanning electron microscopy and nuclear reaction analysis both before and after laser heating. SEM images showed spheres and thin flakes covering the surface which are the areas modified by plasma particles striking under grazing angles. Due to roughness of the surface there are shadowed regions between the 'flakes'. Laser pulses did not lead to expected common ablation of the surface. Features that looked like 'melting' of thin surface layers were rather observed. The initial deuterium content in the surface layer of tiles was of the order of 10^{18} D atoms per cm^2. After the laser light impact the content decreased with 60–70%; by reducing the deposited power by a factor four, the deuterium content was decreased by 40–50%. We make the interpretation that we approach a threshold of the laser detritiation method in fusion devices.

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Keywords: Tritium; Carbon; TEXTOR; Surface analysis; Laser

1. Introduction

Analysis of critical plasma-wall interaction issues for plasma facing components (PFC) in the next step fusion devices [1] led to the formulation of four key problem areas that will affect the design of the fusion reactor. Operation experience with tritium in TFTR and JET showed that without tritium removal, ITER operations could become terminated due to safety and fuel economy reasons [2]. Not going into their comparisons, one can mention that laser-induced desorption was considered as an appropriate tool for the removal of tritium.

Terreault and co-workers were the first who performed, in 1991–1996, a series of works [3–8] on desorption of ion-implanted deuterium using a pulsed ruby laser. These works were laboratory investigations of ion trapping and release. In 1997 Skinner proposed the laser desorption technique as a tool for detritiation of TFTR and JET tiles and extensive research has been made in this direction using a continuous wave Nd laser [9–14]. At JAERI an ArF excimer laser (193 nm, 25 ns,

* Corresponding author. Tel.: +46 8 790 4159 fax: +46 8 249131.
E-mail address: emmoth@imit.kth.se (B. Emmoth).

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0.1–10 J/cm^2) was used for demonstration purposes of the possibility of ablation removal of co-deposits from JT-60 tiles [15–17]. One of the questions of the use of the laser technique for detritiation is the regime of laser operation. Particularly, it was suggested that ablation of the surface by high power laser beam has a negative effect due to possible re-deposition of ablated material and tritium re-trapping in the freshly depleted film. For this reason, pulsed lasers were ruled out of consideration. Recent experiment by Shu led however to the conclusion that redeposition (and hence, re-trapping) can be neglected. Moreover, pulsed laser was proposed for in-vessel detritiation of JT-60 [15–17]. Though many studies were devoted to laser desorption, there is practically no information about transformation of the tile surface subjected to a laser beam. This is why we have started these investigations. The present paper describes the first results obtained on TEXTOR bumper tiles irradiated by a pulsed excimer laser.

2. Experimental

An excimer KrF laser Lambda-Physik COMPex 102 was used in our work. The parameters of the laser are: wavelength 248 nm, pulse duration 25 ns, repetition rate of maximum 20 Hz and the maximum energy 350 mJ per pulse. The irradiation in this work was performed in air, in an out-of-focus position; to increase the irradiated spot and decrease the density of the deposited energy. The spot was about 1.5 cm^2 in area. This gives the energy density of about 230 mJ/cm^2 per pulse (as measured), and the power density of 9.2 MW/cm^2 in the pulse.

The topography of the samples was analyzed by SEM and the deuterium content in the – as exposed and laser irradiated tile, was determined by nuclear reaction analysis (NRA) using a 3He analysis beam at 1.2 MeV. As the reaction cross-sections are known, the quantity of deuterium within the surface layer could be determined. In case of SEM, a ZEISS 942 equipment was used at typical magnifications of up to 20 000 times.

The samples for investigations were cut from tiles taken from the stock of used bumper limiter graphite tiles of TEXTOR. The tile exposure time was over 100 000 plasma seconds, including erosion and deposition effects on the surfaces. The surface of tiles was non-uniform in appearance. Erosion and deposition zones could be distinguished.

3. SEM observations

The original surface of the graphite, which was not in contact with TEXTOR plasma and not irradiated by laser pulses, is shown in Fig. 1. The picture is taken at normal incidence of the electron beam. One can see that the surface is rather rough with a dense small sized relief.

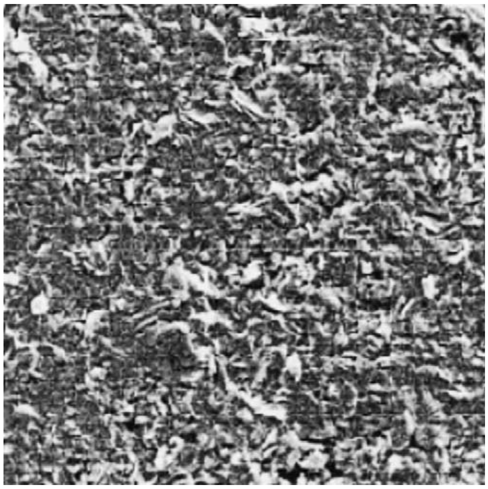

Fig. 1. The original surface of the graphite, which was not in contact with plasma, taken by SEM at normal incidence of e-beam. The picture frame is 60 × 60 μm.

The surface, which was in contact with TEXTOR plasma but was not irradiated by laser, is shown in Fig. 2. One can see that the surface is covered flake-like structures.

The development of the flake-like areas on the rough surface can be explained if we assume that plasma ions come to the surface rotating along magnetic lines inclined to the surface. If the particles come under an angle to the surface, they interact only with the ‘hills’ of the relief surface, which shadow valleys and deeps between them. Therefore, only the ‘hills’ become modified.

Fig. 2. The surface of the graphite, which was in contact with TEXTOR plasma, taken by SEM at normal incidence of e-beam. The picture frame is 60 × 60 μm.

The surface of the tiles exposed to plasma is only slightly colored with a rainbow features, by eye observations. Investigation of the cross-section of the tile by SEM reveals no skin-layer with the properties different from the graphite substrate. Even if it exists, its thickness is of the order of 0.3 μm or less. Laser irradiation of the film gave a change in the surface brightness. The irradiated surface is perceived as being darker in visible light. At the same time it is seen as being brighter in the SEM. These are possibly because the surface topography has become rougher after laser irradiation. The rough surface better absorbs the visible light and emits more electrons.

The SEM observations of the boundary between the original film and the irradiated area demonstrate that the laser irradiation did not lead to expected ablation of the surface. This agrees with the results of Shu, who observed ablation of JT-60 tiles after a threshold of about 1 J/cm^2. Comparison of the features of the two regions shows that there is no principal difference between the original and laser irradiated surfaces in overview images, taken with a low magnification. The laser irradiations were made at the energies of 70 and 230 mJ/cm^2 per pulse. Either 5 or 20 pulses applied. The difference between four spots irradiated by the laser in different conditions is seen well in observations made normal to the surface, as in Figs. 3 and 4. The surfaces look as if laser beam lead to melting of the upper surface layers. But the effect of melting is different. It looks like the melting just start occurring at 70 mJ/cm^2 per pulse. Only the upper layer is melted within 5 pulses. The increase of the shot number to 20 initiate melting of underlying layer in which melting protrudes appear. At the higher energy of 230 mJ/cm^2, the surface looks like a thin top layer of the film is melted and quenched. Due to surface tension, globular- and sponge-like features appear on the surface. Some of the globular features are very bright (higher secondary electron yield). This is possibly due to a decrease of the electric conductivity through the narrow interface between the globule and the substrate. Increase of the number of pulses from 5 to 20 lead also to melting of underlying surface layers. The melted

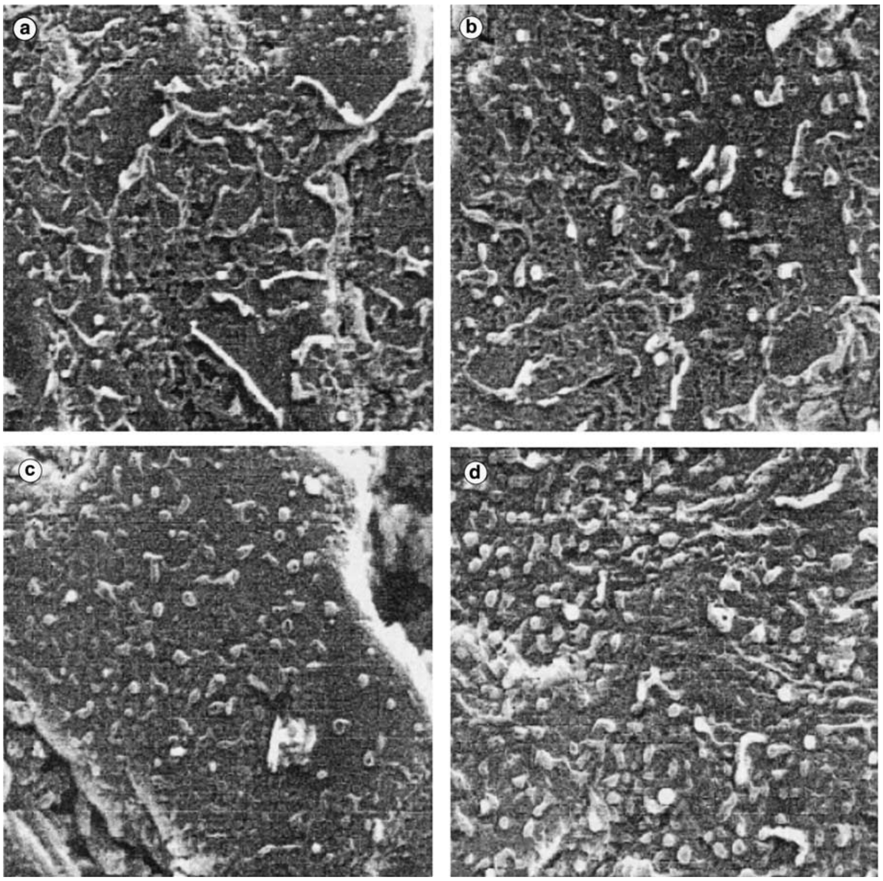

Fig. 3. The surface of the graphite after 5 pulses (a) and 20 pulses (b) of 70 mJ/cm^2 each. The frames of the photos are 15×15 μm. Observation is made at normal incidence of the e-beam.

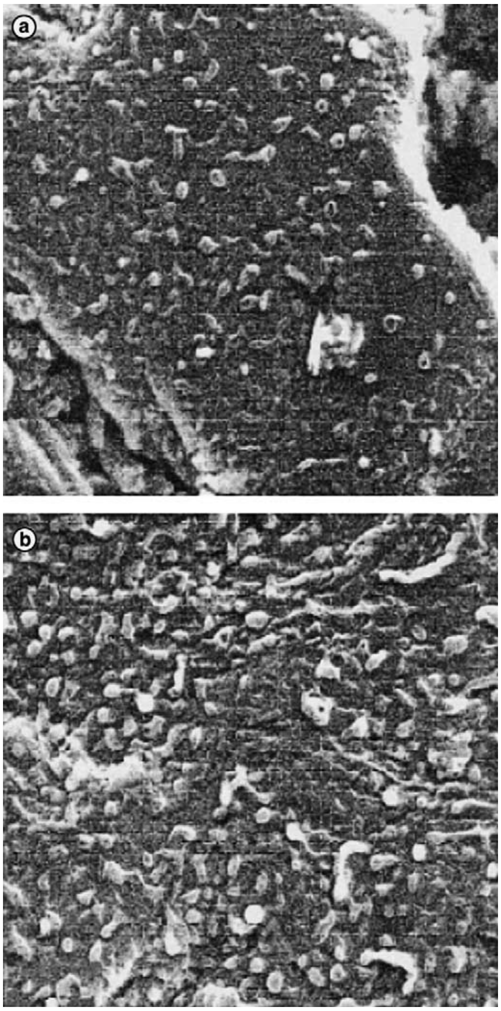

Fig. 4. The surface of the graphite after 5 pulses (a) and 20 pulses (b) of 230 J/cm^2 each. The frames of the photos are 15×15 μm. Observation is made at normal incidence of the e-beam.

structure becomes more developed and gets a spongy appearance. The experiments with the low beam density clearly demonstrate that the modified film consists of very thin layers with a poor thermal conductivity between them. This is why, the small number of shots lead to melting of only a very thin uppermost layer. One can also see that even this low energy beam evaporates some of deposited carbon, though this is not a large-scale effect. Increase of the number of shots at the low beam energy four times (from 5 to 20) has not lead to the proportional increase of the melted substance. This means that conductivities between the layers are different. The conductivities between layers could be different either initially (before laser shots) or changed by a few shots in the beginning of irradiation.

4. Ion beam analysis

The modified layer of the tiles was very thin, around 1 μm. It consisted of carbon, deuterium, oxygen, and metals from the Inconel components (Ni, Cr, Fe) of the TEXTOR liner, as it was determined by RBS. Oxygen was found to be of the order of 10^{18} and metals of the order of 10^{16} (measured in 10^n per cm^2) Carbon could not be determined on top of graphite tiles. Metal atoms constituted the top levels of the graphite tiles. The laser-irradiated samples were mounted in the analysis chamber and the 1.5 mm analysis beam (in diameter and with energy 1.2 MeV) was scanned over the different spots, which were 3 mm in diameter (defined by an aperature limiting the laser beam). At the higher laser energy deposition a reduction in deuterium was observed at about $65 \pm 20\%$ within the irradiated spot. When using the 4 times lower laser energy the corresponding reduction was about 50%. More exact figures are not useful at this early stage of new investigations.

5. Concluding remarks

Samples cut from a bumper limiter tile of TEXTOR were investigated. SEM images of the surface showed that thin flakes covered the surface. At the same time, cross section observations did not reveal the film on the surface due to rather rough analysis beam dimensions. It is supposed that the 'flakes' are the areas modified by plasma particles striking under a grazing angle. Laser heating by 5 to 20 pulses of 25 ns and 70 to 230 mJ/cm^2 each, did not lead to ablation of the surface, apparently. The flaked structure did not disappear, only features that look like 'melting' of thin surface layers were observed. The deuterium content in the layer was reduced by 65% at the higher laser power deposition and with 50% at the lower laser energy deposition.

Acknowledgments

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