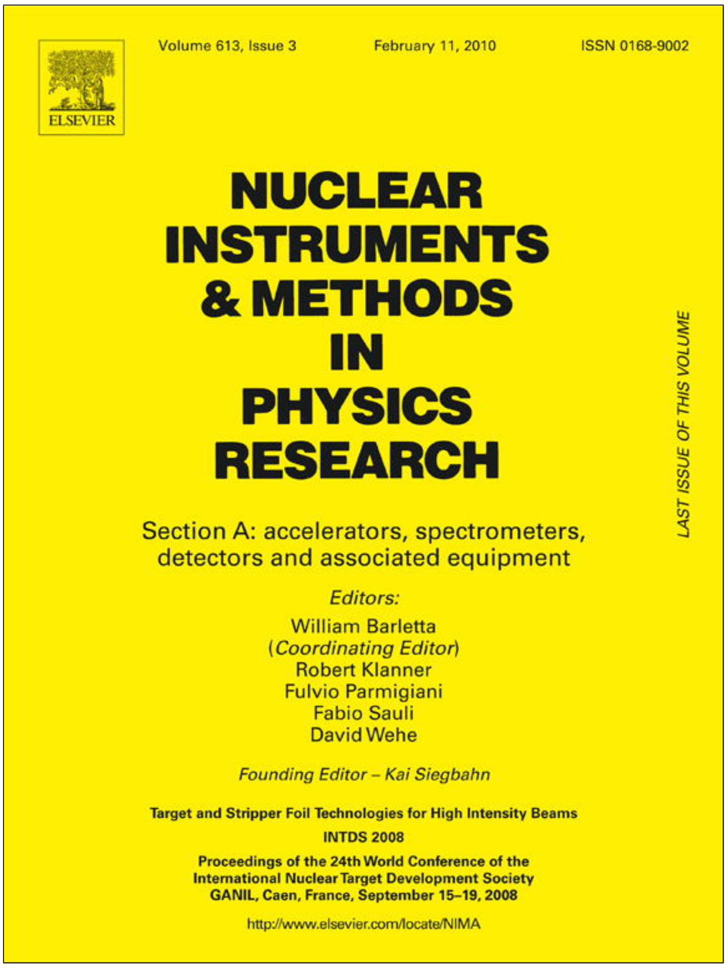
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Investigation of sputtering of thin diamond-like carbon (DLC) target foils by low energy light ions

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ABSTRACT

Along with use for stripping and timing of high energy ions in accelerator experiments, ultra-thin DLC foils are being successfully applied to the instrumentation for fusion and space plasma research. In the latter case, the foils are exposed to light ions and neutral atoms in the keV energy range. Unlike high energy ion irradiations, the foil lifetime is determined by thinning of the foil due to sputtering by particles that transit the foil. In this work, sputtering of thin (1–3 μg/cm^2) DLC foils produced by two different techniques such as modified glow discharge deposition and laser plasma ablation has been investigated using high intensity He$^+$ beams at 4 keV. A loss of foil material under ion impact was estimated from on-line measurements of energy loss of transmitting ions by means of an electrostatic analyzer. For comparison, samples of arc-deposited carbon foils were also evaluated. To avoid any carbon build up on the foils under ion irradiation, the measurements were carried out in an oil-free vacuum environment. Calculated from the measurements, results on both threshold fluence and total sputtering yield of the foils for the incident He$^+$ ions are presented together with some extrapolations to other low energy projectiles of fusion plasma interest. This enables an estimate for operational lifetime of the DLC foils determined by sputtering.

1. Introduction

Thin and ultra-thin (~1 μg/cm^2) diamond-like carbon (DLC) foils have proven to be advantageous over standard carbon foils such as charge stripping targets and secondary electron emitters in many accelerator experiments [1–6]. Also, these foils have become a core technology for a variety of energy and mass analyzers for particle diagnostics of fusion plasmas [7] in particular, at the ITER facility [8]. At MeV beam energies, an operational lifetime of target foils has shown to be limited by ion-induced thickening, shrinkage and tearing caused by radiation effects [9–11]. At these high energies, in which the nuclear stopping power is much less than the electronic stopping power, sputtering plays only a small role in degradation of the foils. However, at the keV energies of neutral particles emitted by fusion plasmas, foil erosion by sputtering is a main contributor to foil failure, since in this energy range the nuclear stopping power is much larger than the electronic stopping power [12].

The intensity of neutral atoms of deuterium bombarding foil targets in ITER is expected to be maximal around 1 keV [8]. This is close to the maximum sputtering yield for carbon bombarded by light ions. Data for sputtering-induced damage to DLC foils by low energy particles, which has not been previously measured, is required to predict the performance of DLC foils in fusion plasma devices under long-term low energy particle irradiations.

The sputtering of thin arc-deposited carbon foils by 20 keV and 40 keV Ar$^+$ bombardment has been measured [12] by comparing the measured angular scatter distribution of traversing 2 keV protons to the proper ion scattering theory.

In this study, we investigate for the first time, the sputtering of very thin novel DLC foils produced by different techniques when exposed to He$^+$ beams at 4 keV. Unlike experiments described in Ref. [12], we applied a more direct method to quantify the sputtering of the foil under ion impact. Our approach is based on the fact that the energy loss of particles transmitted through a thin foil ΔE varies in proportion to the thickness of the foil T in the energy range of interest, i.e. $\Delta E \propto T$ [13]. So that, using the energy loss measurements before (ΔE_0) and after (ΔE_1), an ion irradiation run, one can determine thinning of the foil due to the sputtering, i.e. $\Delta E_0/\Delta E_1 = T_0/T_1$. The experimental data for low energy He ions

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have been extrapolated to hydrogen, deuterium and tritium energetic projectiles relevant to the fusion plasmas.

2. Experimental apparatus and techniques

The experiments on sputtering DLC foils by low energy light ion bombardment were carried out at the MEFISTO test facility of the University of Bern, Switzerland [14] that was found most appropriate for this purpose in view of its dedicated high intensity ECR ion source and oil-free vacuum environment. A schematic of the set-up together with photograph of the experimental arrangement are shown in Figs. 1 and 2, respectively. The foil samples were mounted on a movable holder in front of an electrostatic 90^o energy analyzer with an energy resolution $\Delta E/E \cong 5\%$ and successively exposed to 4 keV He^+ ions with a beam density of 15–20 μA/cm^2. The beam was directed through a 4-mm-diameter collimator (aperture A-1) and onto a 6-mm-diameter foil sample with a secondary electron suppressor (aperture A-2) biased to −18 V to ensure an accurate measurement of the incident ion beam current needed for foil fluence measurements. As mentioned in part 1, sputtering of the foil samples was studied using thickness measurements derived from the energy distribution of transmitted ions obtained with the electrostatic energy analyzer. The energy distribution was measured by recording the current in a shielded Faraday cup at the exit of the analyzer as a function of the applied voltage $\boldsymbol{U}$ between analyzer plates. Starting from an initial value of $\boldsymbol{U}$, the voltage was varied in 1024 steps over an interval $\boldsymbol{\delta U}$ selected to be sufficiently large to cover the entire energy distribution. The current measured at each step was digitalized together with analyzing voltage and properly handled with a PC to directly provide the energy distribution of ions behind the foil with the scanning time of 5 min. Intermittently during He^+ bombardment, the current on the foil target was measured and fluence $\boldsymbol{\Phi}$ was estimated by integrating beam current over the bombardment time and normalizing to the area of aperture A1.

DLC foils of two types with thickness ranging from 1 to 3 μg/cm^2 were used as samples in the sputtering measurements. The first type of DLC foils were produced in the Kurchatov Institute by modified glow discharge deposition as described in Ref. [3]. A second type of DLC foils were fabricated in TRIUMF using the advanced laser plasma ablation method [15]. After floating the foils from the substrates, the foils were picked up on a 10 line-per-mm copper mesh affixed to the foil frame. The thickness (surface density) of the foils before exposure to the beam was determined by weighing the foil samples with an estimated accuracy of

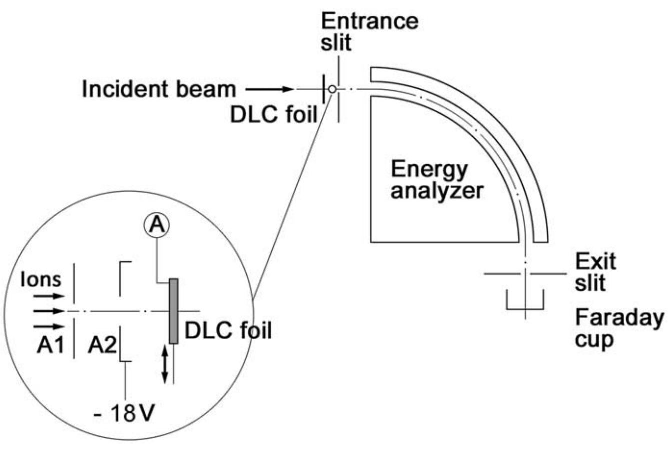

Fig. 1. Schematic of the experimental setup.

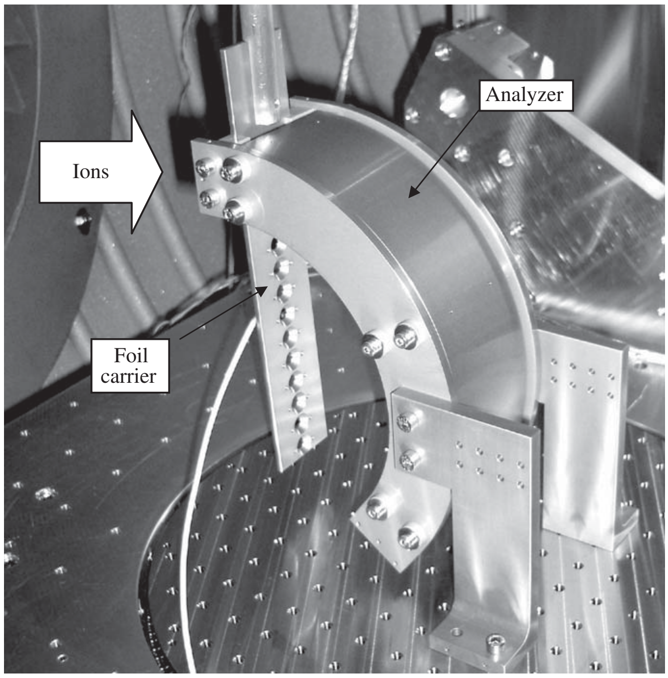

Fig. 2. Photograph of the experimental arrangement in the high vacuum chamber.

approximately 20%. For comparison, we also irradiated several standard carbon foils of the same thickness range, produced by carbon arc discharge. Eleven mounted foils with diameter of 6 mm were fixed at the carrier (Fig. 3) and installed in front of the energy-analyzer as shown in Fig. 2. In total, about 20 different foil samples have been evaluated in two irradiation runs ensuring reasonable statistics.

To avoid any carbon build up at the foils under high intensity ion bombardment, the measurements were carried out in an absolutely oil-free-vacuum environment at a pressure of $\sim 5 \times 10^{-5}$ Pa.

3. Results and discussion

From the measured energy distribution of ions behind the foil, we found a decrease in energy loss with irradiation time that is clearly attributed to thinning of the foil. An example of such measurements is shown in Fig. 4, which depicts the energy spectra of He^+ ions after different time of irradiation. The small high energy peak at the upper energy distribution of Fig. 4 is attributed to the incident ions transmitted through pin holes in the foil, while the peak in the low energy range is found to be due to the "mesh effect" resulting from inelastic scattering of the ions by the grid wires [7]. As the initial energy of the ions can be directly inferred from the spectra obtained by this way, such method makes possible on-line energy loss measurements for ions traversing the foil and therefore to control its sputtering under ion impact by ΔE vs. time measurements. Derived from this data, dependence of the foil thickness on irradiation time is presented in Fig. 5. One can see that the thickness of the foil decreases linearly with increasing irradiation time thus confirming sputtering as a major physical mechanism of degradation of the foil in the described experiments. The average incident fluence required for the removal of 0.1 μg/cm^2 of carbon appeared to be around $\boldsymbol{\Phi}=6.4 \times 10^{16}$ He^+/cm^2 for glow discharge DLC foils as compared to $\boldsymbol{\Phi}=5.5 \times 10^{16}$ He^+/cm^2 for laser plasma ablation DLC foils. Unlike glow discharge and laser plasma ablation DLC foils which showed approximately the same

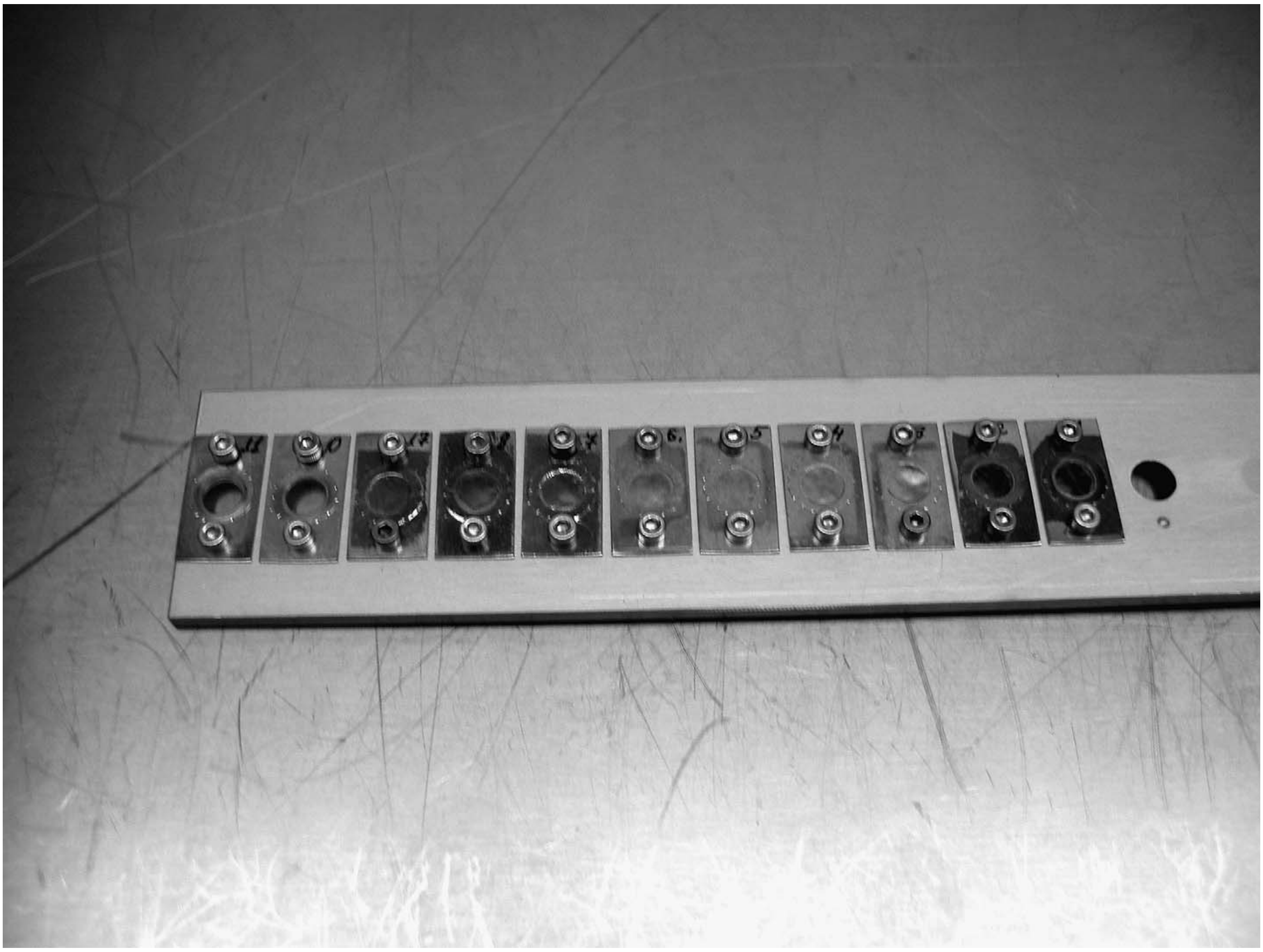

Fig. 3. Test foils on the carrier.

resistance against sputtering by He ions, ordinary arc discharge carbon foils in these conditions exhibited higher sputtering rate by a factor of approximately two. It should be mentioned that no significant formation of holes in the foils was observed at this dose. However, an extremely high fluence bombardment may cause a localized foil tearing that could result from sputtering of thinner region of the foil as well as changes in the foil structure similar to that observed under MeV bombardment [10]. An optical microscope image of the 2 μg/cm^2 foil on a 10 line-per-mm copper mesh after extremely high fluence bombardment is shown in Fig. 6. The creation of tears and holes in the foil was observed to be a threshold phenomenon. The latter is in agreement with the results of Ref. [12].

Based on the foil thickness decrease measurement under given fluence, a mean total sputter yield of investigated very thin DLC foils was estimated to be $\sim$0.20 per incident He$^+$ ion at 4 keV. The primary source of error in this sputtering yield measurement is apparently the accuracy of the applied ion-energy loss-technique that is assumed of up to 20%. Besides, initial sputtering of adsorbed species and residue from foil parting agents can likely over estimate measured data because the adsorbate and residue are easily sputtered as they are lightly bound to the foil.

Since the sputter yield is proportional to the nuclear stopping power of the incident ion in the foil, one can use the SRIM code to calculate the nuclear stopping power of another projectile of interest, and then extrapolate the He$^+$ sputter yield to these different ions. Results of such extrapolation of the sputtering yield for fast atoms of T, D and H at 1 keV, which are supposed to be responsible for degradation of DLC foil targets at the ITER device are presented in Table 1 together with related threshold fluences.

Using calculated data on flux of D–atoms at the ITER of $\sim 10^{11}\,s^{-1}\,cm^{-2}$ [7] and threshold fluences measured in this study (see Table 1), we can then estimate the lifetime of the foils in this device.

Defining lifetime the foils as the time for its 20% thinning due to sputtering we found lifetime of the 2 μg/cm^2 foil to be equal to 2×10^6 s of continuous operation of the ITER device. Since the device is planed to operate in a 20 min-pulse-mode, the foil should withstand 3000 pulses, which is far beyond the accepted operational demands.

4. Summary

We have quantified sputtering of thin DLC foils by light ions in the keV energy range relevant to fusion plasmas. No significant difference in damage to the foils produced by glow discharge or laser plasma ablation foils was observed. However, sputtering rate

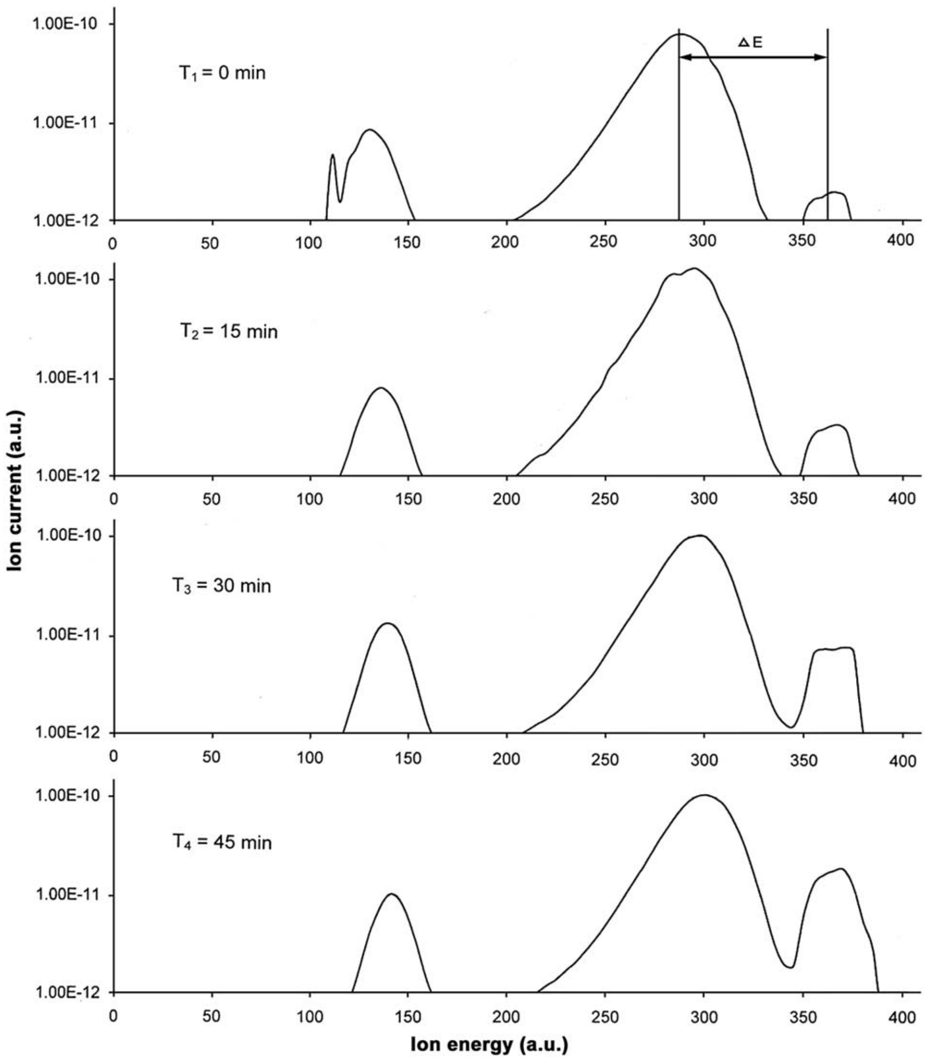

Fig. 4. Energy distribution of He^+ ions behind the 3 μg/cm^2 foil after different times of irradiation. The initial energy of the ions is 4 keV.

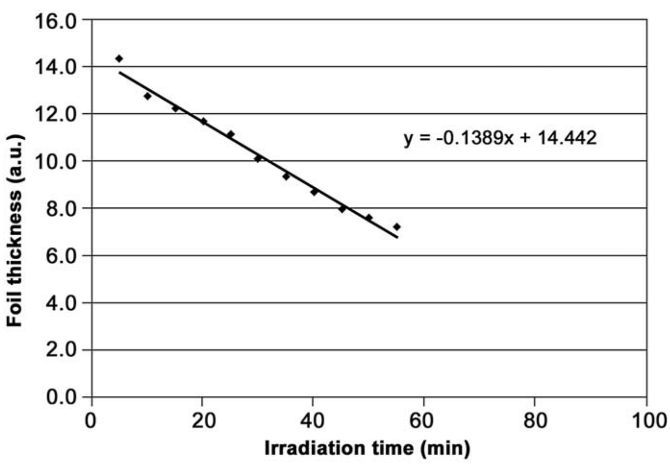

Fig. 5. The foil thickness derived from energy distribution of transmitted ions as a function of the irradiation time.

of standard arc discharge foils was found to be higher by a factor of approximately two.

Based on the measurements and extrapolated data, the lifetime of DLC target foils in the ITER fusion device has been predicted and is far beyond the accepted operational demands.

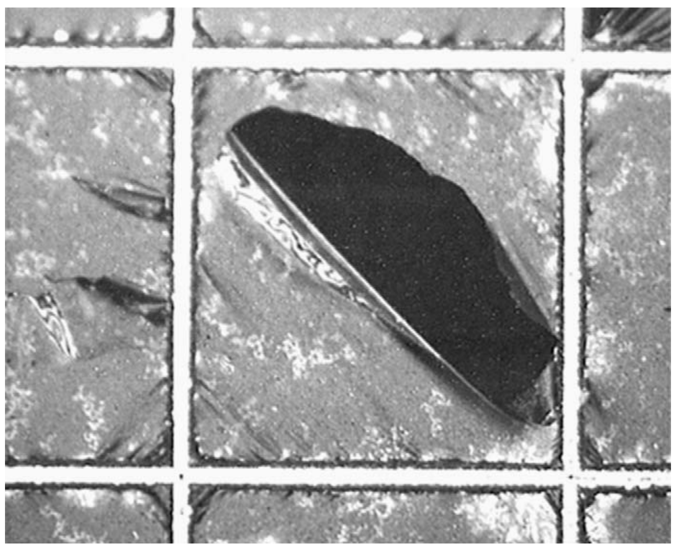

Fig. 6. Optical micrograph of a 2 μg/cm^2 DLC foil on a 10 lpmm (pitch size of 100 μm) copper mesh with the tear caused by extremely high fluence bombardment. Note that even when the foil was forced into failure by ion bombardment, the tear was still confined to the individual pane.

Table 1
Measured (for He) and extrapolated (for T, D and H) values of sputtering yield and threshold fluence of DLC foils bombarded by different projectiles.

Projectile	He	T	D	H
Energy (keV)	4.0	1.0	1.0	1.0
Sputtering yield	0.20	0.16	0.12	0.08
Fluence $\mathbf{\Phi_{0.1}}$	$5.0\times10^{16}\,cm^{-2}$	$6.2\times10^{16}\,cm^{-2}$	$8.3\times10^{16}\,cm^{-2}$	$12.5\times10^{16}\,cm^{-2}$

$\mathbf{\Phi_{0.1}}$ is the fluence required to sputter 0.1 μg/cm^2 (5.0×10^{15} atoms/cm^2) of DLC foil.

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