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LASER CLEANING OF ITER'S DIAGNOSTIC MIRRORS.

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Abstract

Practical methods to clean ITER's diagnostic mirrors will be essential to ITER's plasma operations. We report on laser cleaning of ITER-candidate single crystal molybdenum mirrors that were plasma coated with either carbon or beryllium films 150 – 420 nm thick. A pulsed Nd laser beam was focused to 1-2 J/cm^2 and scanned at various speeds across the surface of a mirror. The cleaning effect was measured with a novel method that combined microscopic imaging and reflectivity measurements in the red, green and blue spectral regions and at the H-alpha and H-beta wavelengths. No damage of the molybdenum mirror substrates were observed at the range of laser intensities used. For carbon coated mirrors, complete removal of the film and restoration of the reflectivity was measured in some conditions. For the beryllium coated mirrors restoration of reflectivity has so far been incomplete. Heat transfer calculations suggest a shorter ~ 5 ns laser pulse would be optimal.

KEYWORDS: diagnostic mirrors, laser cleaning, ITER

18 pages, 8 figures, 1 table,

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I. INTRODUCTION

Over 80 first mirrors are planned for ITER diagnostics that assure machine protection and enable plasma control as well as obtain needed physics data. These are necessarily exposed to plasma deposition and erosion[1,2] that can reduce the mirror reflectivity and impair the function of the diagnostic. Results from JET suggest that degradation of mirror reflectivity could occur in less than 10 ITER discharges in some cases[3,4]. Countermeasures will be vital to sustaining ITER's plasma operations and include limiting mirror exposure with shutters, viewing ducts with small entrance pupils and baffling fins and *in-situ* cleaning with plasmas[5,6] and lasers.

Lasers have been successfully applied to cleaning a variety of surfaces from lithography masks[7] to works of art[8], and were used to detritiate deposits on TFTR and JET tiles[9]. The laser ablation mirror cleaning method aims to exploit the higher optical absorption of a mirror deposit by irradiation with a laser intensity that is above the ablation threshold for the deposit but below the ablation threshold for the mirror substrate (which has a higher reflectivity and hence lower laser absorption). A 1.06 μm laser was used to treat 10 Mo and stainless steel mirrors whose reflectivity was impaired by deposits of beryllium, carbon and deuterium from JET plasmas[10]. To avoid personnel exposure to beryllium the work was done at the JET beryllium handling facility. Some of the Mo mirror reflectivity was recovered by laser treatment - up to 90% of the original value in the infrared region of the spectrum, decreasing to 50% recovery at 400 nm. Pitting of the mirror surface by the laser spot was observed, even though the laser intensity used (5.83 J/cm^2) was lower than the previously measured damage threshold (6.67 J/cm^2) for single laser pulses on Mo. The pitting was attributed to a lower damage threshold for overlapping laser spots in the laser scan. In a different experiment a gold coated polycrystalline Mo mirror was exposed to 2,550 discharges in the HL-2A tokamak[11] resulting in a 1 μm film composed of carbon and hydrocarbons with Si and Fe impurities. The mirror was treated with a Q-switched Nd:YAG laser at 1.06 μm with 100 mJ pulse energy, beam diameter 5 mm, duration 10 ns and repetition rate 1-10 Hz. For this laser pulse the ablation threshold was measured to be 0.6 J/cm^2 and the damage threshold 1 J/cm^2. Up to 90% of the reflectivity was recovered in the infrared wavelength region, but a much lower fraction was restored in the UV and visible region.

II. EXPERIMENTAL SETUP

We report on the application of a scanning Nd laser beam to cleaning molybdenum mirrors with carbon or beryllium deposits. Single crystal molybdenum is the leading material candidate for ITER mirrors as its homogeneous structure provides a high quality mirror surface, polishing technology is developed and it retains its reflectivity well under sputtering conditions[12]. For this work single crystal molybdenum mirrors were supplied by Technical University Applied Physics, Ltd and had a 18 mm diameter reflective surface. They were coated at the PISCES facility at the University of California in San Diego (UCSD) Center for Energy Research[13]. Four mirrors were coated with a 170 nm or 420 nm thick carbon film by a RF plasma source using a methane gas fill. Another three mirrors were coated with 150-200 nm of beryllium using the witness plate manipulator system in the PISCES B linear plasma device[14]. A 2.4 mm wide mask covered a central strip of the mirrors to provide an uncoated reference surface for reflectivity measurements. Previous measurements at UCSD of similar Be coated mirrors showed that high levels of porosity in the coating strongly reduced the reflectivity to levels much lower than the nominal reflectivity of beryllium[15].

A detailed description of the laser scanning and measurement system is given in reference[16]. In brief, the mirrors were housed in a specially designed conflat spool piece with a viewport. To avoid personnel exposure the Be coated mirrors were installed at UCSD and the chamber filled with argon at atmospheric pressure. The mirrors remained sealed in the chamber throughout the measurements and the chamber will be returned to UCSD for disposal. The experimental system provided: (i) high resolution imaging to detect any damage to the mirror surface by the laser but with a large distance (~ 125 mm) between the mirror and microscope objective; (ii) spatially resolved measurements of the specular reflectivity of the mirror surface at different wavelengths before and after (iii) laser treatment of specific areas on the mirror.

A NRC DC-5 stereo digital microscope was used to image the mirrors in the blue / green / red wavelength bands with one pixel corresponding to 4.3 - 17 μm on the mirror depending on the magnification setting. Narrow band reflectivity measurements at 486.1 nm (H-beta) and 656.3 nm (H-alpha) were also performed with optical filters inserted in the optical path. Three coated molybdenum mirrors and an aluminum first surface mirror were mounted in a vacuum spool piece with a viewport at one end. Restoration of reflectivity after laser treatment was

apparent in a brighter image along the laser path. For comparison of the reflectivity changes across the mirror it is important that the illumination field on the mirror be as uniform as possible and this was conveniently achieved with a light bulb with an internal high diffusivity coating. Images of the mirror surface were recorded as .bmp files and an Interactive Data Language (IDL) program was used to extract the intensity data and plot lineouts of the blue/green/red intensity of selected bands on the mirror. The spool piece was rotated on a cradle to bring each mirror into view of the microscope so that the intensity reflected by the reference aluminum mirror could be directly compared to the intensity reflected from the coated molybdenum mirrors. The Mo mirror reflectivity was measured by comparison to the aluminum reference mirror by assuming a 90% reflectivity for the Al mirror, or by comparison to an uncoated region on the Mo mirror.

A multimode 10.6 μm Nd laser with an RF powered Q-switch was used. Typically the pulse repetition rate was 8 kHz, the pulse duration (FWHM) was 220 ns (Fig. 1) with an average power 125 watts. The laser beam was coupled to a scanner via a fused silica fiber (fiber optic coupling from a remote laser to the tokamak vessel will be essential in future applications of laser mirror cleaning to tokamaks and this feature adds realism to the present tests). Two orthogonal mirrors in the scanner steered the laser beam on a trajectory controlled by a computer interface. The scan speed ranged from 80 – 4,082 mm/s giving up to 100 overlapping laser spots. Various focusing lenses were used to give focal spot intensities ranging from 0.3 J/cm^2 to 2.7 J/cm^2. When the laser spot was scanned across an aluminum bracket that was coated with black paint it completely ablated the paint and enabled a measurement of the effective focal spot size of 1 mm (Fig. 2). After a laser scan the mirror chamber was transferred to the microscope for reflectivity measurements.

III. RESULTS

III.A. Carbon Coated Mirrors

Four mirrors were coated by a RF plasma source using a methane gas fill. The average coating thickness was measured with a calibrated Dektak IIa stylus profilometer to be 166 nm, 179 nm, 422 nm and 420 nm respectively on the four mirrors. The coatings had an orange or green appearance and reflectivity measurements confirmed the strong wavelength dependence of a dielectric film. Ideally, for laser ablative cleaning, mirror deposits would be strongly absorbing

in contrast to the mirror substrate that would reflect nearly all of the laser beam. The limited reflectivity of bare Mo (69% at 1.06 μm[17]) and the wavelength dependent reflectivity of the carbon coating is not ideal for this technique.

Fig. 3 shows the result of laser scanning the Mo mirror (#4) coated with 420 nm of carbon. The bluish/green areas are the coated but untreated areas. The broad vertical stripe on the left was masked in the coating process and the reflected intensity represents that from the uncoated molybdenum. The vertical tracks on the right were scanned under vacuum with one pass at 1,286 mm/s (6 overlapping spots) with a laser focal intensity of 1.8 J/cm^2. The reflectivity of the band indicated in Fig. 3 (a) in the red spectral region is shown in Fig. 3 (b). It can be seen that the laser scan successfully restored the reflectivity of the coated region to the same $\approx$ 60% level of the uncoated stripe on the left. Similar results from laser scanning Mo mirror #1 coated with 166 nm of carbon are shown in Fig. 4. For this coating the largest loss in reflectivity is in the blue spectral region, and the lineout (Fig. 4(b)) shows complete restoration of the reflectivity at 486 nm after laser scanning under vacuum at 1.8 J/cm^2 and scan speed 1,286 mm/s. Faster scan speeds were also effective as shown in Fig. 5 in a close-up of a laser track scanned at 1.8 J/cm^2 and 4,082 mm/s where the individual laser pulses are visible.

In some cases incomplete film removal was observed. Fig. 6 shows the result of a laser scan at 1.7 J/cm^2 and 340 mm/s on 420 nm carbon coated Mo mirror #4. In contrast to Figs. 4,5, this was laser scanned in air at atmospheric pressure, however film charring was observed in some cases (not shown here) and subsequent scans were done under vacuum. In Fig. 6 the film appears to have peeled back from the substrate. Laser cleaning by a buckling mechanism is modeled in detail in ref. [18]. Previous work has shown that film removal by this mechanism can begin at a fluence as low as 50 mJ/cm^2. In this process, the pressure of gas in the cavities at the film-substrate interface and cavity size increases. In addition, thermal expansion causes the film to curve and detach from the substrate surface. The process can be considered as the generation of thermal compression stress and its transformation into film displacement. In our case we postulate that the differential laser absorption by the carbon film and substrate leads to thermal stress, film buckling and detachment. Since this process can occur at relatively low laser fluences and can cleanly separate a film from its substrate this process is of considerable interest for laser cleaning of diagnostic mirrors.

III.B. Beryllium Coated Mirrors

Three Mo mirrors were coated with beryllium and installed in a sealed chamber that was filled with argon, along with an aluminum reference mirror. The Be coating thickness was measured by a calibrated Dektak IIa stylus profilometer to be 150 – 200 nm. The coating was grey in appearance and showed none of the interference colors apparent in the carbon films. Fig. 7 shows the results of a one-pass laser scan with a focal intensity of 1.6 J/cm^2. The scan parameters are given in Table 1. Partial restoration of reflectivity occurred in some regions, (R=25% increased to R=37%) but the effect resembled melting and sagging of the coating. Increasing the laser fluence by overlapping 5 consecutive laser scans at the lowest speed caused blackening of the film. Increasing the laser intensity up to the maximum of 2.7 J/cm^2 (not shown) did not improve the situation and also caused blackening of the film (not shown). Alloys and eutectics of beryllium and molybdenum are known to exist[19]. Chemical reactions between molybdenum and beryllium have been investigated in connection with the compatibility of the structural material Mo with the neutron multiplier Be at the maximum operation temperatures of a fusion reactor blanket[20] and are possible at temperatures over 800 °C. This reaction could be related to the darkening of Be coated Mo mirrors under some laser conditions.

IV. THERMAL ANALYSIS.

While the present laser pulse is clearly able to ablate black paint (Fig.2) the beryllium results above prompted a re-evaluation of thermal behavior the beryllium film under laser scanning. An analytic heat transfer equation[21] was used to model the 2.7 J/cm^2 200ns FWHM pulse, available from the present acousto-optic Q switched laser and for comparison a lower energy, but higher power pulse at 0.7 J/cm^2 and 5 ns duration available with a Pockel cell Q switched laser[22]. Heat transfer into a substrate can be modeled by:

$$\theta = \frac{2F}{K}\left\{\left(\frac{\kappa t}{\pi}\right)^{1/2}\exp\left(\frac{-x^2}{4\kappa t}\right) - \frac{x}{2}\,\mathrm{erfc}\,\frac{x}{2\sqrt{\kappa t}}\right\} \tag{1}$$

where Θ is the temperature, F the heat flux, K the thermal conductivity, k the thermal diffusivity, x the distance into the surface, and efrc the complimentary error function. This is a simplified zero order estimate that neglects the temperature dependence of thermal coefficients and the heat

of melting and boiling. The beryllium thermal coefficients are taken from ref. [23]. The laser time history (Fig. 1) is approximated by a 200 ns square pulse with energy the same as that incident in the first 200 ns of the laser pulse, reduced by 50% to account for reflection. The results of the calculations are shown in Fig. 8. Curve (a) represents the 1.6 J/cm^2 case of Fig. 7, and curve (b) the same case but with the thermal coefficients arbitrarily reduced by 50% to approximate a porous film. The heat is absorbed to a depth much thicker than the film thickness and this limits the temperature rise. Curve (c) illustrates a lower energy, but shorter duration heating pulse: 0.45 J/cm^2 absorbed in 5 ns. In this case the heat is absorbed in the top 100 nm – a much better match to the coating thickness, and the peak temperature exceeds the Be boiling temperature, as appropriate for laser ablation. We conclude that laser cleaning systems for diagnostic mirrors should aim for a laser pulse length of order 5 ns to efficiently heat or ablate the ~ 100 nm films that affect optical absorption.

V. SUMMARY.

Practical methods to clean ITER's diagnostic mirrors will be essential to ITER's plasma operations. A scanning Nd laser was used to treat ITER-candidate single crystal molybdenum mirrors that were plasma coated with either carbon or beryllium films 150 – 420 nm thick. The carbon coating had a strong wavelength dependent reflectivity, while the beryllium coatings appeared grey. A novel method was used to measure the reflectivity with spatial resolution across the mirror and without personnel exposure to beryllium. No damage of the molybdenum mirror substrates was observed at laser intensities up to 2.7 J/cm^2. Laser ablation was observed on the ideal case of black painted aluminum. Complete carbon film removal and restoration of the reflectivity was observed at 1.7 J/cm^2 laser fluence and the evidence suggests that thermal stress and film buckling was the film removal mechanism. In contrast, the beryllium coated mirrors exhibited incomplete reflectivity restoration or in some cases, film blackening that may be a result of chemical reactions between the Be film and Mo substrate at elevated temperatures. One-dimensional thermal modeling shows that the 220 ns laser pulse used heats the mirror to depth over 1000 nm, far beyond the thickness of a film that affects optical reflectivity. This excessive volume limits the temperature rise. In contrast the modeling showed a 5 ns pulse at lower energy of 0.45 J/cm^2 heated a 100 nm Be film to above the Be boiling point and is a much better thermal match to ablation of ~ 100 nm mirror coating.

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Table 1 showing the laser parameters for the labeled tracks in Fig. 7.

Track	c	d	e	f	g	h	i	j	k
Focal intensity J/cm2	1.6	1.6	1.6	1.6	Un-coated	1.6	1.6	1.6	1.6
Scan speed mm/s	1286	643	321	161		80	80	80	80
# passes	1	1	1	1		1	1	1	5 (1/min)
overlapping laser pulses	6	13	26	55		110	110	110	110

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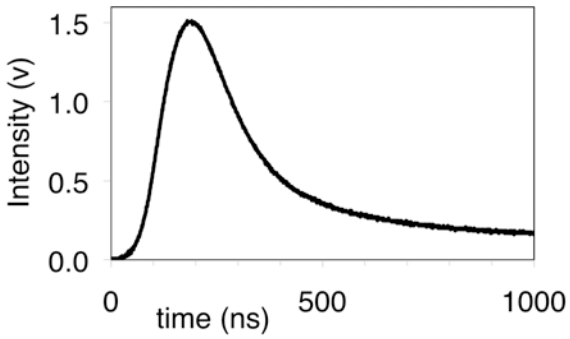

Fig. 1 Laser time history.

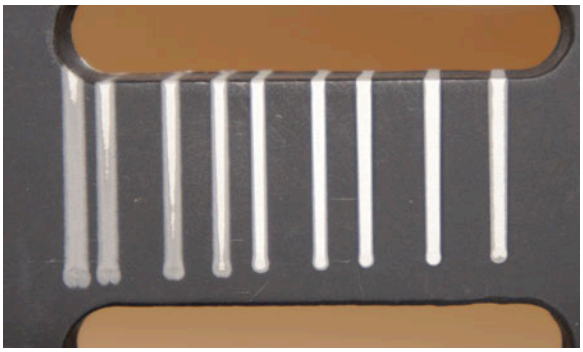

Fig. 2. Laser ablation tracks on an black painted aluminum surface created by translating the surface through the laser focus. The laser peak intensity is 1.8 J/cm^2 and the width of the smallest track 1 mm.

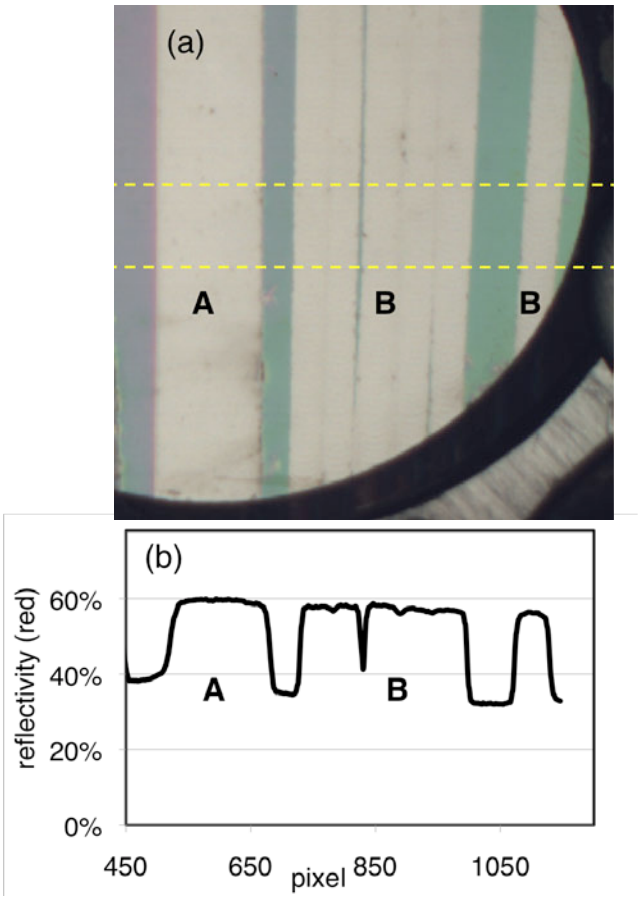

Fig. 3(a) Partial image of 420 nm carbon coated Mo mirror #4 showing uncoated stripe on left labeled 'A', the green coated areas and six strips treated by laser labeled 'B'. The laser intensity was 1.8 J/cm^2 scanned in one pass at 1,286 mm/s. The reflectivity of the area between the dashed lines is plotted in 3(b) and shows good restoration of reflectivity by the laser.

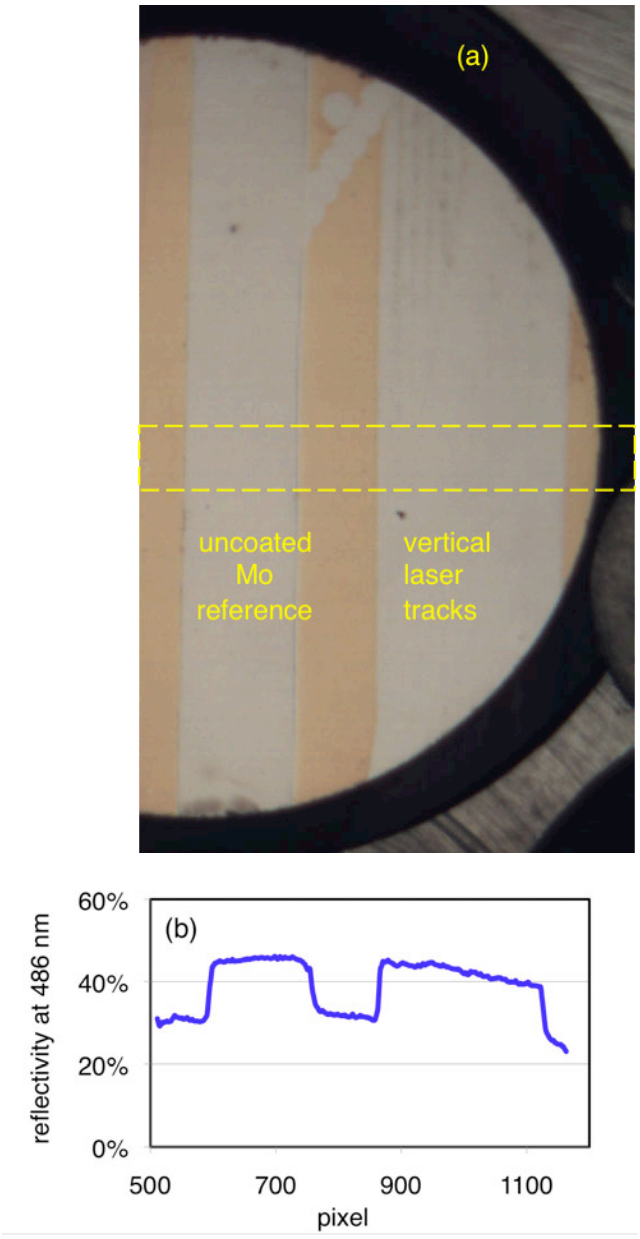

Fig. 4(a) 166 nm carbon coated Mo mirror #1 exposed to laser scan at 1.8 J/cm^2, and scan speed 1,286 mm/s; 4(b) lineout of region of mirror between dashed lines showing uncoated reference and cleaned mirror with good restoration of blue (486 nm) reflectivity. The diagonal track is imaged at higher resolution in Fig. 5.

Fig. 5 Individual laser pulses at 1.8 J/cm^2 are effective at cleaning a 166 nm carbon coating as shown in the diagonal track. The broad band on the left is the uncoated reference.

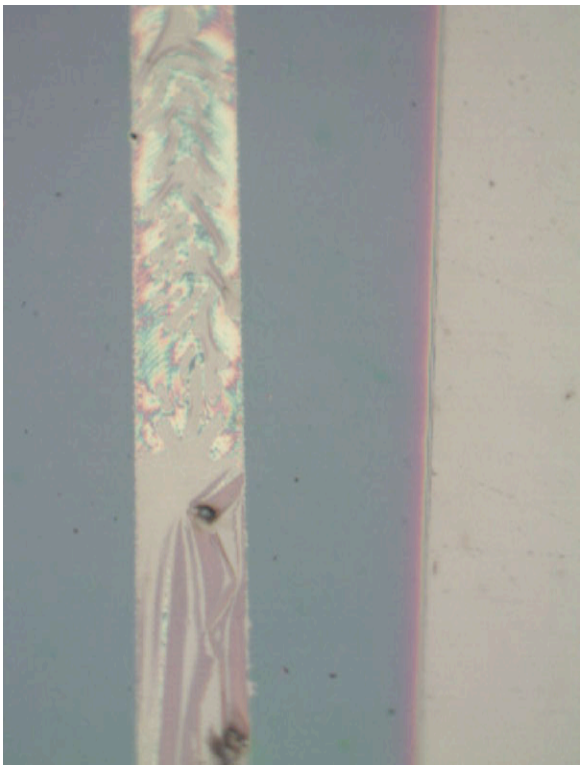

Fig. 6 Film peeling observed after a laser scan 1.7 J/cm^2, 340 mm/s in air. The uncoated reference strip is on the right.

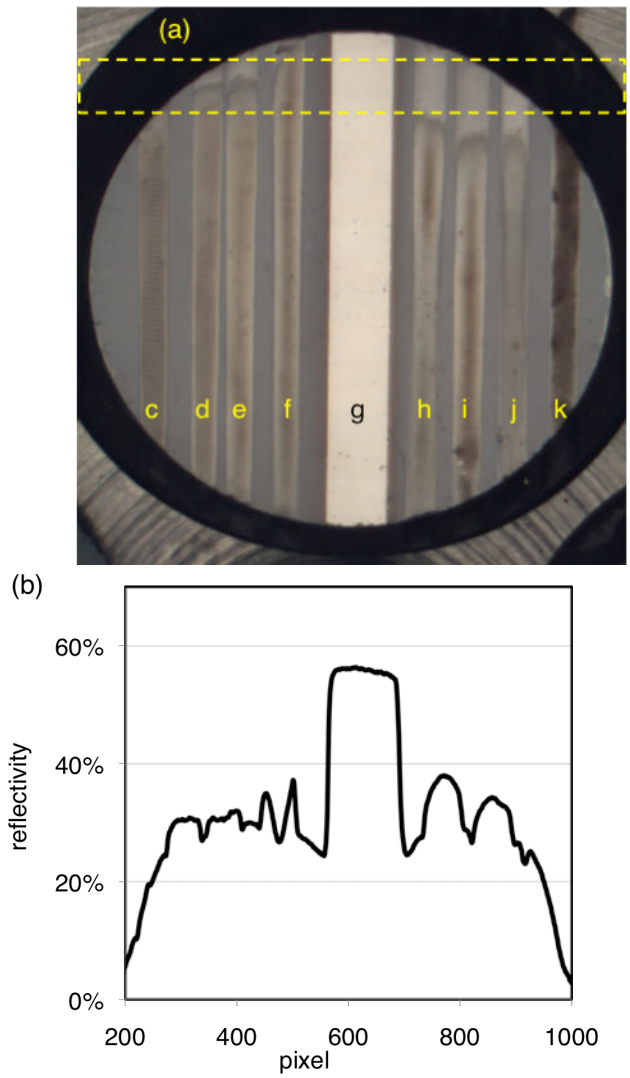

Fig. 7(a) Be coated Mo mirror #5 with an uncoated strip 'g' in the center and tracks from 8 laser scans at 1.6 J/cm^2. The scan parameters are given in Table 1. The reflectivity of the band outlined with a dashed line is shown in Fig 7 (b) and is averaged over the red/green/blue spectral regions.

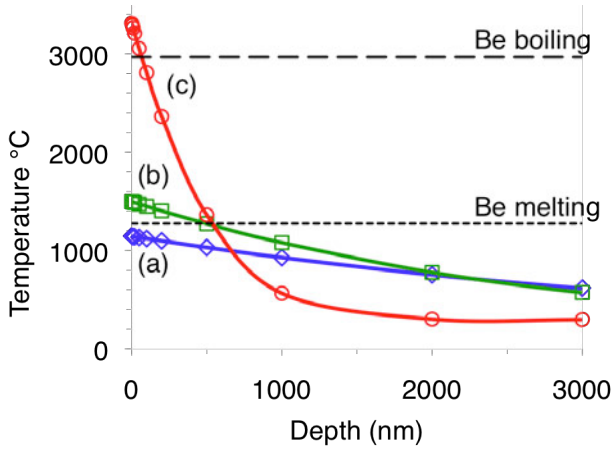

Fig. 8 Heat transfer profiles for (□) curve (a) present 1.6 J/cm^2 laser pulse on Be, (◊) curve (b) present laser pulse on a porous material with thermal coefficients reduced to 50% of Be, and (○) curve (c) a shorter heating pulse 5 ns duration, 0.45 J/cm^2.

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