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ABSTRACT
Our studies were aimed to determine the damage threshold of Molybdenum (Mo) and Stainless Steel (SS) mirrors to provide the maximum fluence which the mirror surfaces could withstand without affecting their reflectivity properties. A high repetition rate ytterbium fiber laser (20kHz, 1.06μm, 120ns) was applied. The experimental single-pulse and multiple-pulse damage thresholds were obtained. To calculate damage thresholds, a 1D analytical model which takes into account the temperature dependent absorptance and multiple pulse damage based on plastic deformations accumulation was applied. The experimental damage thresholds and the theoretical ones are in a good agreement. Cleaning tests with the contaminated mirrors exposed in JET have been performed.

1. INTRODUCTION
Plasma characterization is required for efficient fusion reactors operation. It may be provided via metallic mirrors and optical windows. However, plasma erosion and material deposition results in decrease in mirrors reflectivity [1, 2]. To retrieve their optical quality, the mirrors should be cleaned from time to time.

A laser cleaning of contaminated Mo and SS mirrors which have been exposed to tokamak plasmas was studied in [1, 3-5]. Although the obtained results were promising, further investigations are required to study the effect of semi-transparent deposited layer on heating rates and damage thresholds.

Our studies were aimed to determine the damage threshold of molybdenum (Mo) and Stainless Steel (SS) unused mirrors. The results obtained may be applied to consider the most appropriate laser cleaning features.

2. THEORY AND CALCULATION
In this work, it is supposed that irreversible damage occurs when the surface temperature T becomes equal to the material melting temperature T_m. This assumption could be somewhat optimistic in some cases because damage could appear before T_m due to phase changes or oxidation. To calculate the damage threshold fluence, we have to solve the heat conduction equation with the appropriate initial and boundary conditions [6]. For a metallic target, the approximation of surface heating can be used because the radiation absorption length is much smaller than the laser beam radius and the characteristic heat diffusion length $l = \sqrt{4\,\kappa\tau}$. For laser pulse with a Gaussian spatial profile and a rectangular pulse of duration τ, the temperature T on the surface at the center of the beam is [7]

$$T(\tau) = \frac{(1-R)\,f_0}{ka\pi^{3/2}}\ arctan\ \frac{\sqrt{4\kappa\tau}}{a} \tag{1}$$

where $\kappa = k/\rho c$ is the thermal diffusivity, f_0 is the laser power, a is the laser beam radius at the $1/e$ intensity, R, k, ρ, c are the reflection coefficient, the thermal conductivity, the density and the specific heat capacity of the target material, respectively.

For short pulse duration $\tau << a^2/4\kappa$, the 1D approximation is valid and the temperature on the surface is

$$T(\tau) = \frac{2\,(1-R)\,f_0\sqrt{\tau}}{ba^2\pi^{3/2}} \tag{2}$$

where b = $\sqrt{k\rho c}$ is thermal effusivity.

In many cases, the most significant discrepancy between the experimental data and the model results occurs due to temperature dependence of the material absorptance. The analytical solution of the 1D heat conduction equation for this case was obtained in [8].

The temperature dependence of the absorptance is supposed to be a linear function of the surface temperature $A(T_s) = A_0 + A_1 T_s$, where A_0 is the absorptance at room temperature. In this case, the surface temperature increase at the end of pulse with duration t is

$$T(t) = \frac{A_0}{A_1}\left[e^{u^2}(1 + \mathrm{erf}(u)) - 1\right] \tag{3}$$

where $u = \frac{IA_0}{k}\sqrt{\kappa t}$ and I is the laser radiation intensity. And the damage threshold can be determined as [8]

$$F_{th} = \frac{uk}{A_1}\sqrt{\frac{\tau}{\kappa}} \tag{4}$$

where u is a solution of equation (3) for $T = T_m$.

Thus, it is necessary to know the value of A_1 to calculate laser heating of the mirrors. There are no direct measurements of A_1, but for Mo it can be obtained from the temperature dependence of spectral emissivity [9-13]. The values obtained from different sources can be very different and can even have different signs, but in the majority of cases A_1 is negative. The mean value $A_1 = -3.9\cdot 10^{-5}$ k^{-1}calculated from [9] was chosen.

To the best of our knowledge, there is no experimental data on the temperature dependence of the absorptance or emissivity for SS (and particularly for AISI 316L) at 1.064 μm. But the measured λ_x (X point, for more information see [12, 13]) of major components of SS, namely iron, chromium and nickel, are higher than 1.06 μm and we can suppose that λ_x of SS is also higher than 1.06 μm [13]. Thus, absorptance of SS should decrease with temperature, which means that $A_1 < 0$.The value of A_1 will be evaluated below on the basis of experimental results.

For repetitive laser treatment, the damage threshold may be affected by two phenomena. The first one is the heat accumulation resulting from inequality of initial temperature field for the consecutive laser pulses. For metals, this effect is negligible due to their high thermal conductivity. The second phenomenon is the decrease in damage threshold due to plastic slip deformation accumulation on the surfaces under multiple-pulse irradiation that results in the increase in surface roughness and absorbed laser energy [14-16]. The multiple-pulse threshold depends on single pulse threshold and number of pulses as

$$F_N = F_1\,N^{s-1} \tag{5}$$

where N is the number of pulses, F_N is the N-pulse threshold, F_1 is the single pulse threshold and s is the exponent specific to the material.

This model was applied to study the multi-pulse Mo damage thresholds [17, 18]. The exponent of accumulation curve was estimated as $s = 0.8877$.
To our knowledge, there is no data on this exponent for SS in literature . From the classical mechanical-fatigue data we obtain, $s = 0.88414$ [19], $s = 0.788$ [20] and $s = 0.87696$ [21]. We will use the averaged value $s = 0.8497$.

If the material in the solid state at the temperature T_p undergoes first-order phase transition, it absorbs some amount of energy and its thermophysical properties change. This phenomenon will affect heat conduction in the material and may change damage thresholds.

For Mo, there are no first order phase transitions up to the melting point. For SS, first-order phase transitions occur only at ~1300°C and their latent heats are not high enough to change strongly the damage threshold. Thus, we will neglect the presence of phase transitions in SS in this study

The material properties applied to calculate the damage thresholds are summarized in Table 1. With these data, single-pulse thresholds can be evaluated as $F_{Mo} = 6.6$ J/cm^2 and $F_{SS} = 6.6$J/cm^2 for Mo and SS mirrors, respectively. The multiple pulse thresholds for a number of pulses $N = 5000$ decrease to $F_{Mo} = 2.56$ J/cm^2 and $F_{SS} = 0.33$ J/cm^2, respectively.

3. EXPERIMENTAL SET-UP AND RESULTS

Molybdenum and stainless steel 316L unused mirrors (not exposed to JET plasma) were under our experimental investigations. The mirrors were of 10mm×10mm×10mm dimensions with one optically polished surface (0.02–0.06 μm roughness). It was anticipated that the experimental tests would provide the maximum fluence that the mirror surfaces can withstand without reflectivity properties deterioration.

For the experiments, a pulsed ytterbium fiber laser with pulse duration of 120ns (FWHM) and a repetition rate of 20kHz is applied. The laser beam is focused on the surface of the mirror by a lens with a focal length $f = 420$mm. The diameter of laser spot on the surface is ~100μm at the $1/e$ intensity. The laser power can be adjusted in P = 5÷20W range. The experimental set-up contains a scanning system to allow the laser beam movement along the target surface at a controlled speed. To measure the damage thresholds, the surface of each mirror is scanned by the laser beam by lines. Each line corresponds to a different laser power. The scanning speed is high enough to ensure that each pulse produces individual spot on the surface and that these spots do not overlap.

These damage spots were analyzed with an optical microscope. Figure 1 shows the spot size as a function of the laser fluence ($F = E/\pi A^2$). With this graph, the damage thresholds were determined as the abscissa of a point where the spot size becomes zero.

One should note that there are stop points where the scanning system stops laser beam for about 0.25 second and the mirror receives about 5000 pulses at the same place. These spots are larger than single pulse spots and they were used to determine multiple-pulse thresholds.

For the Mo mirror, the damage thresholds are $F_{sp} = 6.46$ J/cm^2 and $F_{mp} = 3.1$ J/cm^2 for single pulse and for multiple pulses, respectively. For the SS mirror, single pulse damage threshold is F_{sp} = 2.26 J/cm^2 and the multiple-pulse damage threshold was not determined experimentally as it was lower than the minimal fluence provided by our laser system.

By fitting the theoretical single pulse damage threshold to the experimental one, we have determined coefficient $A_1 = -1.21 \cdot 10^{-4}$. For this value, the multiple-pulse damage threshold for SS mirror becomes F_{mp} = 0.64 J/cm^2.

The spots on the mirrors surface were measured also with an optical profilometer MicroXAM 100 (Phase Shift Technology). On the SS mirror surface, conventional crater structures have formed. On the Mo mirror surface, the spots profile from multiple pulses were of a form of a protuberance of about 4–5μm in height with a shallow ditch along the perimeter thus confirming plastic deformation accumulation theory.

The Energy Dispersive X-ray Spectrometry (EDS) analysis of the spots with the scanning electron microscope JEOL JSM-7000F did not reveal any oxidation after laser treatment.

On the basis of damage thresholds measurements, cleaning regimes were chosen for experiments in JET Beryllium Handling Facility with contaminated mirror samples exposed in JET [26]. In these experiments, the same laser system was used with a 50μm scanning step between pulses and rows. The laser fluence ranges were 1.17–2.25 J/cm^2 and 2.80–6.34 J/cm^2 for SS and Mo mirrors, respectively.

The deposited layers on the mirrors had thicknesses between 0.07 and 0.74μm. The amount of Be was varied in the range $0-0.59 \cdot 10^{18}$ atoms/cm^2 with Be/C ratio ranging from 0 to 0.97. The deuterium amount was varied in the range (0.017–15.2) atoms/cm^2.

After the laser cleaning tests, the reflectivity measurements and nuclear reaction analysis were performed. The reflectivity after the cleaning process was found to be better in the infrared region, up to 90% of initial values for both types of mirrors. At 0.4μm, the reflectivity recovers to 35–50% of initial values for SS and Mo mirrors.

The best average cleaning efficiency was obtained for Mo mirror with deposited layer thickness of 0.07μm at 3.92 J/cm^2 with 15 scans. The mirrors with thicker layers show worse recovered reflectivity.

It was found that even keeping the laser fluence below single pulse thresholds it was possible to bring about a noticeable change to both the Mo and SS mirrors. This is associated with the presence of absorbing deposits, overlapping of subsequent pulses and performing several cleaning passes. Despite that the experiments have shown good reflectivity recovery rate for mirrors, 90% of the original reflectivity was regained in the infrared spectrum and from ~35% to ~80% was recovered in the visible spectrum on both SS and Mo mirrors.

DISCUSSION AND CONCLUSIONS

In this study, the analytical model for a quick estimation of the damage thresholds for metallic mirrors was described. This model includes a heating model with temperature dependent absorptance [8] and model of multiple pulse damage based on plastic deformations accumulation [14-16] to estimate damage threshold.

The experimental single-pulse (2.3 J/cm^2 for SS and 6.5 J/cm^2 for Mo) and multiple-pulse (3.1 J/cm^2 for Mo) damage thresholds were obtained.

Single-pulse experimental damage thresholds of Mo and SS mirrors can be compared with ones available in literature using the following relation for threshold fluence [8]

$$F_{th} \sim \sqrt{\tau}/A_0 \tag{6}$$

For our experimental conditions, F_{th} = 6.3±1.3 J/cm^2 for Mo from [27] and F_{th} = 2.1±0.2J/cm^2 for SS from [28] can be obtained. These values are in a good accordance with our experimental and theoretical results.

The application of the theory with changing absorptance and the phenomenological theory of plastic deformation accumulation allow us to predict accurately the Mo damage thresholds. For SS, the theoretical threshold was fitted to the experimental one and the coefficient $A_1 = -1.21 \cdot 10^{-4}$ K^{-1} was evaluated.

Subsequent cleaning tests of Be/C contaminated mirrors exposed in JET show good reflectivity recovery rates in infrared spectral range [26]. But the damage of mirror surface was observed, despite the fact that fluence was below the obtained single pulse damage threshold. Thus, the effect of semi-transparent deposited layer on heating rates and on damage thresholds must be investigated additionally. For example, further improved model should take into account certain complex phenomena, such as complex temporal profile of laser pulse (which may cause errors up to around 20% [7]) and temperature dependence of thermo-physical substrate properties.

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	Mo	SS
Density, kg/m^3	10220	7990
Thermal conductivity, W/m·K	138	21.4
Specific heat capacity, J/kg·K	250	500
Thermal diffusivity, 10^{-5} m^2/s	5.4	0.54
Melting temperature, K	2890	1658
Reflection coefficient A_0	0.69	0.67
Coefficient A_1, K^{-2}	$-3.9 \cdot 10^{-5}$	–
Exponent s	0.8877	0.8497

Table 1: Properties of molybdenum and stainless steel at room temperature [11, 22-25]

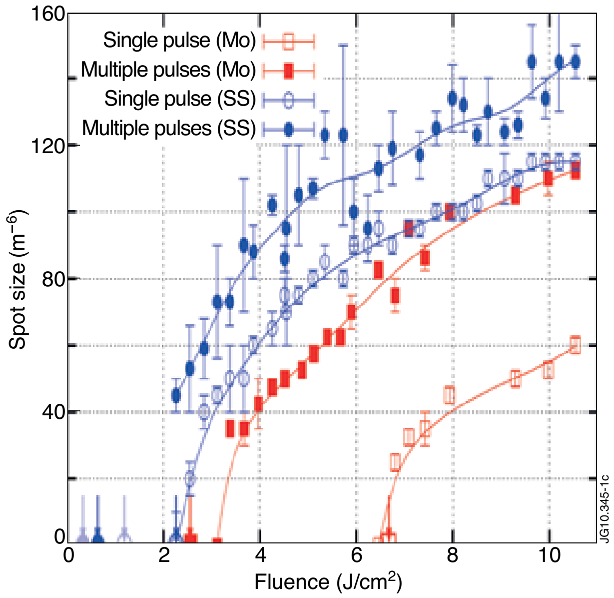

Figure 2: Damage spot size as a function of laser fluence Theoretical damage thresholds are indicated by arrows. Semitransparent arrow correspond to the case $A_1 = 0$.

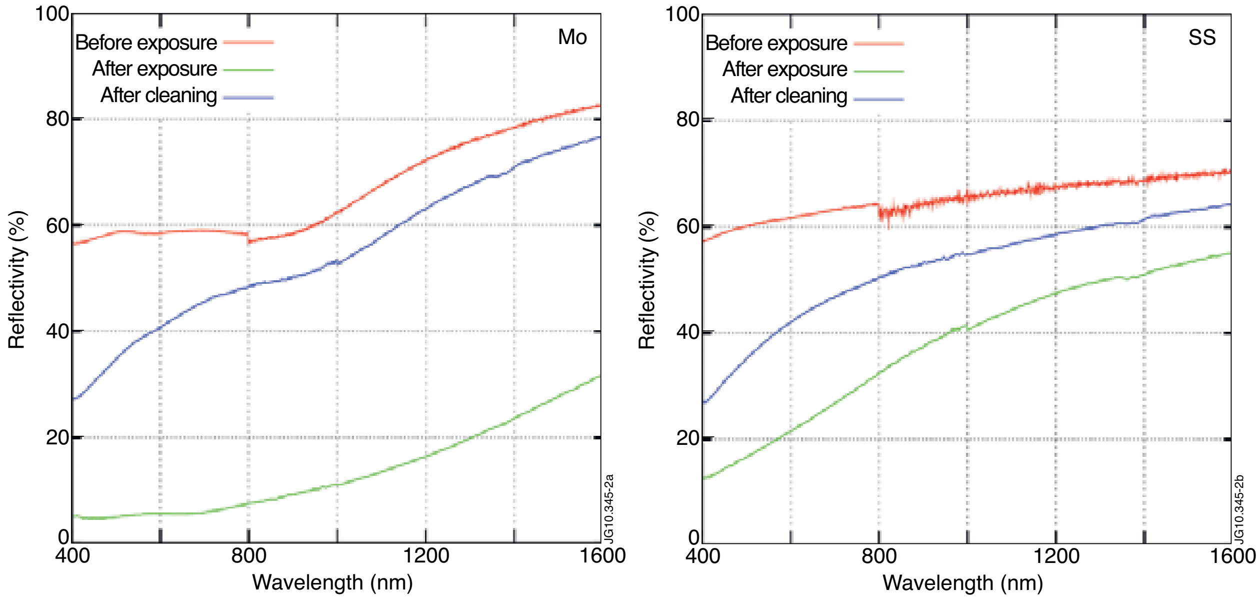

Figure 2: Spectral reflectivity of Mo and SS mirrors.