

LASER-INDUCED DAMAGE OF METAL MIRRORS UNDER LONG-TERM EXPOSURE AT SHALLOW ANGLE OF INCIDENCE

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Abstract— Laser induced damage (LID) experiments were performed with a 2-J frequency-multiplied Nd:YAG laser at $\lambda = 1.06\ \mu\text{m}$ wavelength and a variety of metal mirrors (pure and impure diamond-turned) at shallow angle of incidence to study the sensitivity of these mirrors to LID under long term exposure. Practical lifetime curves for Al-1100 and 99.999% pure Al mirrors have been established up to 10^4 shots of operation. The results show general agreement with theoretical predictions.

I. INTRODUCTION

Metal mirrors have been proposed as a robust final optic for laser-IFE power plants [1]. In order to overcome their inherent limitations on reflectivity and damage fluence, operation using S-polarized beams and a shallow angle of incidence is considered essential. The damage threshold is predicted to exceed $5\ \text{J}/\text{cm}^2$ at angles exceeding 80° , whereas the normal incidence damage threshold for Al at UV is only $\sim 0.2\ \text{J}/\text{cm}^2$.

Operation beyond the normal-incidence damage threshold raises questions of the stability of the surface to long-term exposure. Repeated short-pulse laser irradiation induce repeated thermal stresses that can accumulate plastic deformations and fatigue cracks at the surface. Thus, the long-term damage threshold could be substantially lower than the single-shot value. Today, the fundamental mechanisms of laser induced damage for multiple-shot of exposure are not very well understood and there is a need for further experimental and modeling work to illuminate this subject. In this paper, experimental measurements and associated modeling are performed to verify the higher anticipated damage limit with grazing incidence and to study the sensitivity of the LIDT to long-term operation. Special attention will be devoted to the effect of impurities on the LIDT of metal mirrors.

II. GRAZING INCIDENCE LIDT FOR METAL SURFACES

The variety of proposed and observed damage mechanisms (slip, melting, vaporization, etc.) makes it difficult to universalize a unique criterion for damage in a metal surface. Instead, damage thresholds corresponding to each of these mechanisms have been introduced [3]. A common denominator among all of these damage mechanisms is the dependence on the energy absorbed per unit area of the surface (surface fluence), regardless of the incidence angle. Therefore, for a beam incident on a metal surface at an angle of incidence θ , each of these damage thresholds (for a single laser pulse) must be modified to account for two factors; (1) the surface fluence should be reduced from the fluence normal to the

beam, F_0 , by a factor $\cos(\theta)$. The $\cos(\theta)$ factor is due to the increased surface area irradiated by the rotated beam; (2) the surface reflectivity ($R(\theta)$) and hence the surface absorptance ($A(\theta) = 1 - R(\theta)$) should be modified according to Fresnel equations. For an S-polarized laser beam incident on a metal surface at an angle of incidence θ with a complex index of refraction, $\hat{n} = n + ik$, the absorptance, $A_s(\theta)$ is

$$A_s(\theta) = 1 - R_s(\theta) = 1 - \left[\frac{n^2 + k^2}{n^2 + k^2 + 2n \cos(\theta) + \cos^2(\theta)} \right] \quad (1)$$

Taking the above two factors into account, it turns out that for any specific type of damage;

$$LIDT|_{\theta} = LIDT|_{0^\circ} \left[\frac{A_s(0^\circ)}{A_s(\theta) \cos(\theta)} \right] \quad (2)$$

For a smooth pure Al mirror, and a green laser beam at room temperature, $\hat{n} = 0.85 + i6.46$ and the reflectivity for 85° is 0.99305 and the value of the factor in brackets is ~ 127 . The measured reflectivity of Al-1100 at the same angle of incidence showed a value of 0.9881. Based on the consideration of thermal stress due to pulsed heating, the threshold for plastic deformation is directly related to the temperature rise caused by the absorbed laser energy on the surface. The surface yield temperature rise is given by [2]

$$\Delta T_y = \frac{(1 - \nu) Y}{\alpha E} \quad (3)$$

where ν is Poisson's ratio, Y is the yield stress, E is Young's modulus, and α is the coefficient of thermal expansion. For an S-polarized beam and an angle of incidence θ , the normal beam fluence corresponding to the plastic (slip) threshold is given by Musal [2] as

$$F_y = \frac{5}{4} \left[\frac{2\sqrt{2}}{3} \right]^{3/2} \frac{\alpha^{1/2} (Y/E)^{1/2} t_p^{1/2}}{2 A_s(\theta)} \frac{\Delta T_y}{\cos(\theta)} \quad (4)$$

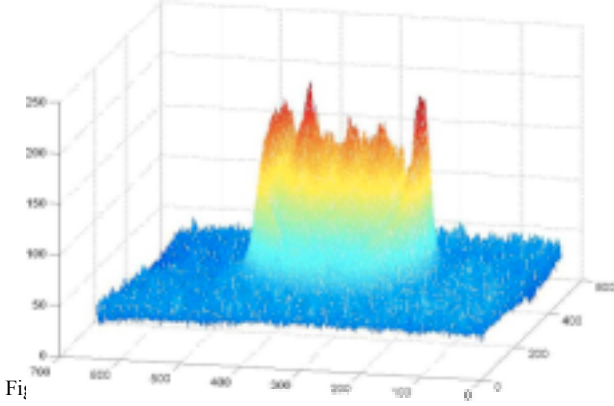
Plastic deformations are expected to accumulate for temperature rises of $\Delta T > 2\Delta T_y$ [2]. In general, the optical absorptance, A , is temperature-dependent, however, a first-order calculation can be performed by assuming no temperature dependence of the material properties. The fluence required to produce melting in this case for an angle of incidence θ , can be given by

$$F_m = \frac{(T_m - T_0)}{2 A_s(\theta) \cos(\theta)} \sqrt{\rho C t_p} \quad (5)$$

III. EXPERIMENTAL PROCEDURE

A. Beam Profiling and Reflectivity Measurements

In LIDT measurement for grazing incidence, the beam profile is of critical importance. Measuring the beam profile enables one to study the local effects on the optic surface. Figure 1 shows the beam profile measured from our YAG laser. It is apparent that the profile is far from the ideal Gaussian and flat top profiles used by in previous studies. The data have been captured using a CCD camera and processed using MATLAB. The Peak-to-Average ratio of the beam intensity has been found to be 4.2. Work is ongoing to smooth the beam and to considerably reduce this ratio.



For pure Al the reflectivity of the tested surfaces can be calculated using the material complex index of refraction and the incidence angle. For impure Al samples, such an optical property is not known and a Cavity-Ring-Down-Reflectometer (CRDR) is used to measure the samples' reflectivities to a high accuracy (100 ppm). The CRDR uses two partially reflective spherical mirrors in addition to the test mirror. The laser pulse enters the cavity as shown in Figure 2. A small fraction escapes during each pass and is detected in a fast photodiode. The pulses decay with a time constant related to the reflectivities of the two output couplers (known) and the test mirror. A typical example of the CRDR oscilloscope trace is included in Fig. 2.

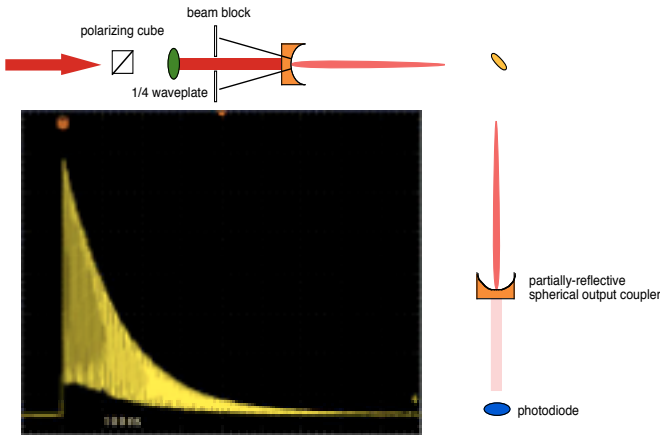


Figure 2. Cavity Ring-Down Reflectometer and a Typical Trace of the Oscilloscope Signal.

B. Experimental Setup and LIDT Measurements

The experimental setup is shown schematically in Figure 3 where the original beam is allowed to pass through a polarizing cube. The P-polarized beam goes to the beam dump

while the S-polarized beam is sampled to measure the spatially averaged energy (for single shot) and power (for repetitive shots) per unit area of the beam. The average beam energy is measured using a thermopile detector. After passing the beam sampler, the main beam is focused using a 30 cm lens and is incident upon the test sample at an angle of 85 degree. The mirror surface intersects the focused beam and the footprint of the beam is an ellipse with a non-uniform surface fluence, as shown schematically in Fig. 3. Using the measured beam profile, geometry and the measured average energy/power, the fluence distribution over the ellipse surface can be determined. The expected fluence distribution is shown schematically in Fig. 3. The surface fluence distribution was measured by imaging impurity scattering from the exposed mirror surface using a CCD camera as shown in Fig. 4.

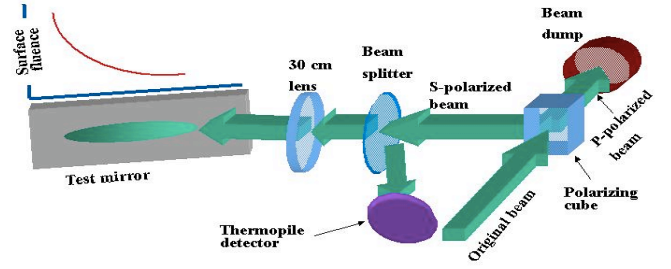


Figure 3. A schematic diagram of the experimental setup and fluence distribution across the exposed sample surface.

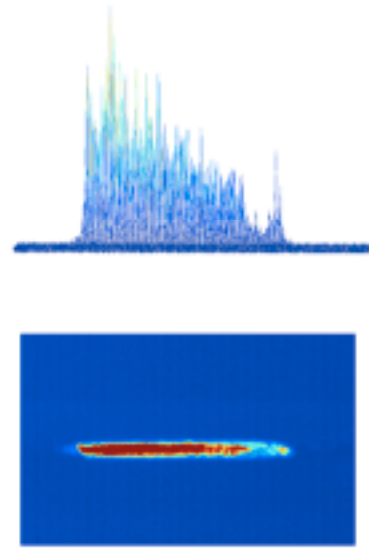


Figure 4. Surface fluence distribution captured using a CCD camera.

Experiments have been performed at 85° , for single and multiple shots using a 532 nm, S-polarized laser beam. For each experiment, the normal beam fluence is measured and each tested sample is inspected for visible damage, and reflectivity change. Scanning electromicrographs and optical microscopy images of the mirror surface have been used to investigate the fine-scale details of the damaged locations.

IV. RESULTS AND DISCUSSION

A. Observed Types of Damage

Different damage phenomena have been observed and were found to depend on the surface fluence as well as the amount of impurities contained in the mirror composition. Three types of Al mirrors have been investigated; 1- Al-6061 (98% Al and 2% impurities); 2- Al-1100 (99% Al and 1% impurities) and 3- 99.999% pure Al mirrors. Both Al-6061 and Al-1100 have shown a whitish type of damage at relatively low fluences. This type of damage has not been reported in previous studies (see for example [3]) and has been found to be due oxidation of the impurities on the mirror surface. Figure 5 shows a typical SEM micrograph at low magnification for a whitish damaged caused in an Al-1100 mirror by 2000 pulses at 24 J/cm² normal to the beam. The chemistry profiles for different locations in the undamaged region, A, (including impurities locations) show no oxygen content. However, similar chemistry profiles have been taken for other locations in the damaged region, B, and show the presence of considerable Oxygen content at the impurities locations only. It is concluded that this type of damage is an oxidation of the impurities on the mirror surface. Similar results have been obtained for Al-6061 samples, which confirmed the above conclusion. Figure 6 shows a 500X micrograph of a damaged area of an Al-6061 sample exposed to a 100 pulses at fluence < 1 J/cm². Three locations have been chosen in this damaged area to study their chemical composition. Spots 1 and 2 represent rough damaged locations while spot 3 represents a smooth undamaged location. The chemistry profiles of these locations are shown in Figs. 7-a, 7-b, and 7-c, respectively. The high oxygen content is easily recognizable for spots 1 and 2 while no oxygen content is detected for spot 3 in agreement with the aforementioned explanation.

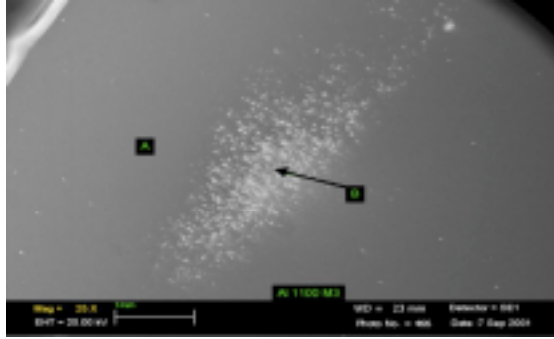


Figure 5. Oxidation damage of Al-1100 caused by 2000 pulses @ 24 J/cm².

With 99.999% pure Al mirrors, no oxidation has been observed, however, slip lines, melting and ablation occurred at relatively higher fluences. Fig. 8 shows an optical microscopy image of a 99.999% pure Al surface that has been exposed to 10⁴ shots at 71 J/cm². Superimposed on image is a magnified SEM micrograph of the melting zone. Slip lines and melting zones as well as an intermediate transition region can be easily recognized in the image.

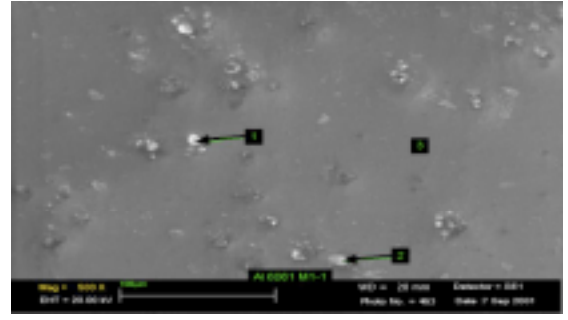


Figure 6. Oxidation damage of Al-6061 caused by 100 pulses and fluence < 1 J/cm².

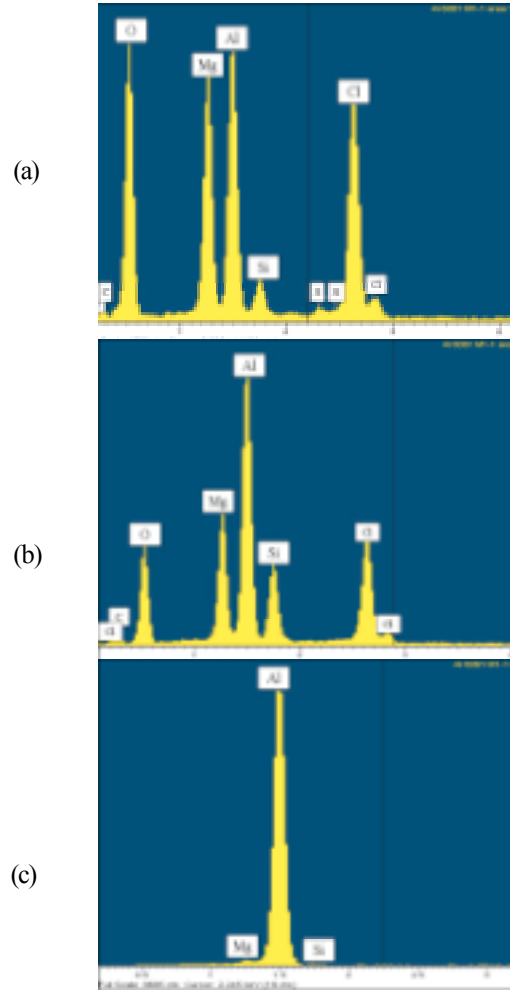


Figure 7. Chemistry profile of locations 1,2, and 3 shown in Fig. 6.

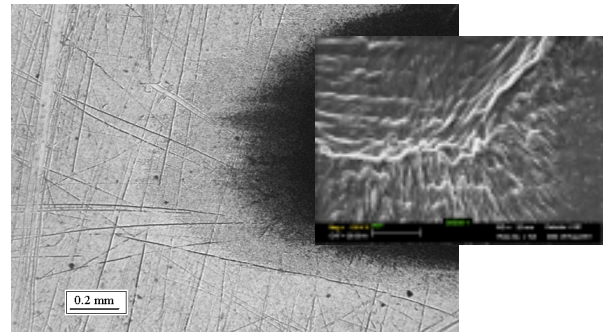


Figure 8. Slip lines and melting for a 99.999% pure Al mirror.

B. Lifetime Curves

Practical lifetime curves (fluence vrs. no. of shots) have been constructed for Al-1100 and 99.999% pure Al mirrors through a series of single-spot experiments. Damage has been defined as either oxidation or melting whichever occurs at lower fluence. Figure 9-a and 9-b show the practical lifetime curves in terms of safe (no damage is observed) and unsafe (damage has been detected) regions for Al-1100 and 99.999% pure Al mirrors, respectively for 532 nm and 85°.

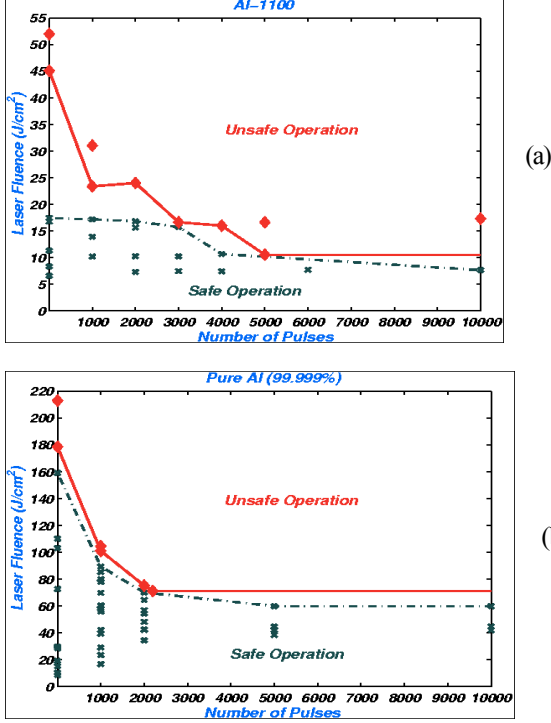


Figure 9. Practical lifetime curves for Al mirrors at 532 nm and 85°.

C. Comparison with Theoretical Expectations

Simple estimates of the slip and melting damage thresholds have been calculated using equations (4) and (5) for a single pulse irradiation and compared to experimentally measured damage fluences. Thresholds for cumulative plastic deformation have been also estimated and compared to the damage fluences at 10^4 shots where, at such high number of shots, catastrophic failure occurs due to cumulative plastic deformation. Using equation 2, and considering the pulse length, calculated and measured damage thresholds from Ref.3. for normal incidence on pure Al mirrors are translated the corresponding values at 85° for comparison with the present results. Table 1 summarizes these comparisons and from which it can be seen that, because of the oxidation of the surface, Al-1100 fails at a fluence much less than the melting threshold for the single pulse case and similarly it fails at 10^4 at fluences less than the threshold for cumulative plastic deformation. Results for 99.999% pure Al showed good agreement with the melting threshold for the single pulse case, however, for multiple pulses the measured damage fluence was higher than the predicted one by a factor of 2. Discrepancies between measurements and predictions can be attributed to neglecting the spot size effect through the use of the 1-D model equations given above as well as the temperature dependency of the material properties. Pure Al mirrors showed

much higher damage threshold compared to that of Ref. 3 while Al-1100 showed comparable values to that of Ref. 3 (in which composition of the mirror surface was not reported).

Table 1. Comparison between theoretical predictions and experimental damage fluences.

		Al-1100	99.999% Pure Al	Ref. 3 @ 85°
Single shot (J/cm²)	Slip, F_y	9.6	16.5	1.136
	Melting, F_m	125	215	66.45
	Measured, F_0	45	159	19.31s 42.6m
	F_y/F_0	0.213	0.104	0.059
	F_m/F_0	2.778	1.352	1.56
Multiple shots (J/cm²)	Measured, F_{10^4}	10.53	71.1	-
	$2 F_y/F_{10^4}$	1.823	0.464	--

V. CONCLUSIONS

Damage thresholds have been determined for single and multiple pulse irradiations of Al mirrors at shallow angle of incidence (85°). Decreasing the impurities content in the Al mirrors reduces surface oxidation and dramatically enhances the damage thresholds. The results showed and confirmed the expected dramatic increase of the damage thresholds of Al mirrors at grazing incidence compared to normal incidence. The experimental results were compared to model expectations and results of other authors and showed general agreement within the uncertainty margin of the simplified assumptions of the model 1-D model used for theoretical predictions.

ACKNOWLEDGMENT

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