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Abstract

Measurement of the waist diameter of a focused Gaussian-beam at the $1/e^2$ intensity, also referred to as spot size, is key to determining the fluence in laser processing experiments. Spot size measurements are also helpful to calculate the threshold energy and threshold fluence of a given material. This work reports an application of a conventional method, by analyzing single laser ablated spots for different laser pulse energies, to determine the cross-sectional area of a focused Gaussian-beam, which has a nominal pulse width of ~10 ps. Polished tungsten was used as the target material, due to its low surface roughness and low ablation threshold, to measure the beam waist diameter. From the ablative spot measurements, the ablation threshold fluence of the tungten substrate was also calculated.

1 Introduction

The characterization of laser systems is important for understanding the effects of the laser parameters (e.g. wavelength, pulse duration, and spot size) on the ablation mechanisms. The ablation mechanism of a given material can occur by photothermal, photochemical, or photophysical ablation, and generally depends on the wavelength and pulse duration of the laser beam. Different ablation mechanisms will produce different characteristics in the ablation damage, given the type of substrate, e.g. metals and polymers. The properties of a substrate determine how the irradiated light interacts with the surface and how the light is absorbed. In order to compare results found in the literature, which report threshold fluences given a specific substrate and laser characteristics, it is key to determine the spot size and consequently, the cross-sectional area of the focused laser beam. Fluence is an important parameter and is calculated as the amount of energy irradiated on a surface per unit area. Several reports in the literature have addressed the determination of Gaussian laser beam spot size [1–5], even for two-dimensional energy distribution [6].

In this work, the area of a focused Gaussian picosecond laser beam is determined by exposure of ultraviolet single-shot laser pulses on a tungsten substrate. A conventional method [3, 4] is employed to measure the one-dimensional diameter of the beam waist ($1/e^2$) by analyzing single laser ablated spots for different laser pulse energies. The results include the measurements of the dimensions of the ablated craters. The ablation threshold of tungsten is determined by single-shot picosecond laser pulses.

2 Experimental

2.1 Materials

Tungsten polycrystalline substrate (MTI Corp.) was used for the determination of the focused laser beam area. The tungsten substrate had two sides polished, nominal purity of 99.95%, and nominal average surface roughness of less than 30

Å. The surface characteristics of the tungsten substrate provided a homogeneous surface to clearly measure the ablated crater dimensions.

2.2 Laser Ablation

The schematic diagram of the laser system is shown in Figure 1. The single-shot ablation was performed with a Nd:YVO$_4$ (Atlantic 20-355, EKSPLA) laser, which was operated at 355 nm with a nominal pulse duration of ~10 ps. The laser beam was focused by an f-theta lens (S4LFT6062/075, Sill Optics), with an effective focal length of 250 mm, for a wavelength of 355 nm. The laser source operates at TEM$_{00}$ beam mode. The TEM$_{00}$ laser beam passes through optical components before being focused by the f-theta lens. The laser system was assembled and calibrated by PhotoMachining Inc. The average laser power was measured with a thermopile sensor (30A-BB-18, Ophir-Spiricon) and a laser power meter (Nova II, Ophir-Spiricon). The laser ablated spots were produced by moving the XY translational stage to expose a fresh surface after each single laser shot.

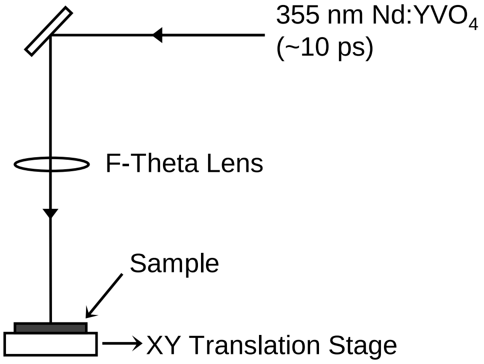

Figure 1. Schematic of the picosecond laser system for ablation of the tungsten sample.

2.3 Ablation Spot Analysis

The surface morphology analysis was performed using a JEOL JSM-5600 scanning electron microscope (SEM) operated at an accelerating voltage of 15 kV. The dimensions of the ablated spots were measured by analyzing the SEM micrographs using the image processing and analysis software ImageJ [7].

3 Results and Discussion

Figure 2 shows the SEM micrographs of the ablation craters for the pulse energies of 5 µJ, 15 µJ, and 30 µJ. The contours of the ablated craters exhibit smooth edges. This demonstrates that there is no thermal damage or redeposited material around the craters. As the laser energy increases, the shape of the ablated crater diverges from an ellipse. In addition, the absorption of the laser pulse at the center increases and produces an inner crater with a more consistent elliptical shape. The inner crater can be evidently observed in Figure 2c. The inner crater in Figure 2c also presents smooth edges. Above 15 μJ, the craters exhibit a deformation, which may be due to a distortion in the spatial laser energy distribution. The contours of ablated craters exhibit effects of astigmatism, which produces an elliptical shape. Different angles of divergence in two transverse directions cause astigmatism and elliptical beams [8–10]. Despite the drawback of the crater shapes ablated above 15 μJ, Figure 3 shows the closest elliptical fit to the crater contours. Figure 3a shows that the ablated crater was easily fit, however in Figures 3b and 3c, the elliptical fits became more challenging. From the elliptical fit (red contour) shown in Figure 3, consider D_1 as the minor diameter (green chord) and D_2 the major diameter (yellow chord).

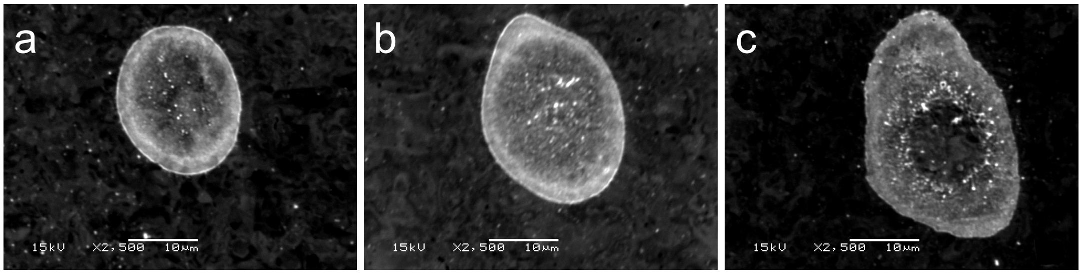

Figure 2. SEM micrographs of craters ablated at a) 5 μJ, b) 15 μJ, and c) 30 μJ.

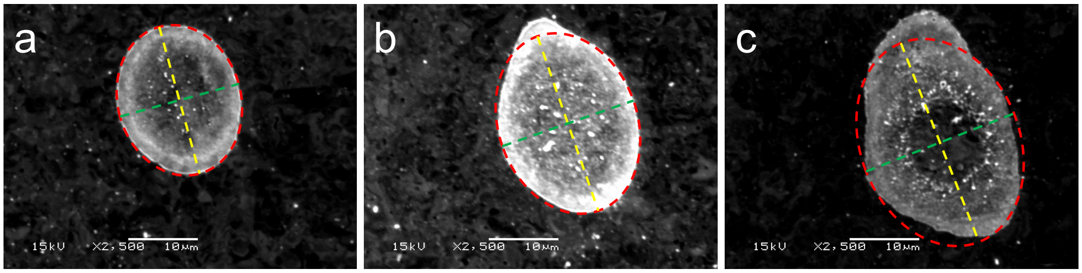

Figure 3. SEM micrographs with measurements of the elliptical fits to ablated crater contours, a) 5 μJ, b) 15 μJ, and c) 30 μJ. The green chord is the minor diameter, and the yellow chord is the major diameter.

Theoretically, the diameter of an ablated spot can be calculated by [11]:

$$D^2 = \frac{D_0^2}{2} \ln\left(\frac{E}{E_{th}}\right) \tag{1}$$

where D is the diameter of the ablated crater, D_0 the diameter at the Gaussian beam waist, E the irradiated pulse energy on the material, and E_{th} the ablation threshold of the material. The optical diameter D_0 represents $1/e^2$ of the intensity peak value. Within the circle of radius $w(z)$, 86% of the laser beam power is carried. At the waist, $z = 0$, the radius is $w(0) = D_0/2$.

From the SEM micrographs, it is clear that the Gaussian beam distribution is two-dimensional. Considering the minor diameter axis to be x and the major axis to be y, the two-dimensional Gaussian intensity (irradiance) at the beam waist is given by:

$$I(x,y) = I_0 \exp\left(-\frac{2x^2}{w_{0x}^2}\right) \exp\left(-\frac{2y^2}{w_{0y}^2}\right) \tag{2}$$

where I_0 is the peak intensity at the center of the beam and w_0 is the Gaussian beam radius, at which the intensity drops to $1/e^2$ of its peak intensity. The peak of the two-dimensional Gaussian function occurs when both radial positions, x and y, are on the center axis of the beam, i.e. $(x, y) = (0, 0)$.

Figure 4 shows the single-shot laser ablation threshold measurements of tungsten. Each data point is an average of three measurements, and the error bars indicate 1σ standard deviation. The logarithm of the ratio of E to E_{th} is linearly proportional to D^2. From the logarithmic fit to D_1, $E_{th,1}$ = 0.34 μJ. Likewise, for D_2, $E_{th,2}$ = 0.8 μJ. Since the threshold for D_1 is smaller than that for D_2, D_1 is used to determine the ablation threshold energy, E_{th}, needed to produce ablation damage on the tungsten substrate. Therefore, $D_0 = D_1 = 2w_{0x}$. Consequently, $E_{th} = E_{th,1}$ = 0.34 μJ.

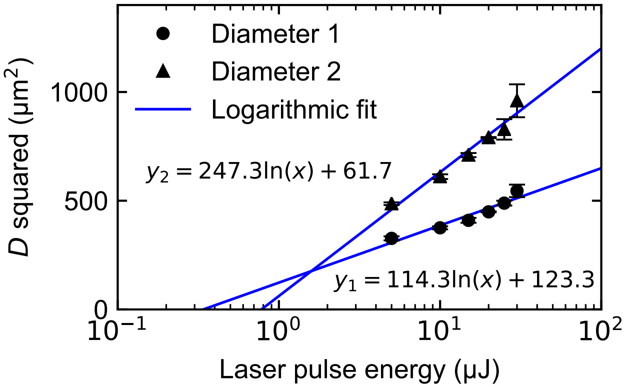

Figure 4. Single-shot laser ablation threshold measurements of tungsten. Diameter 1 is referred to as D_1, the minor diameter, and Diameter 2 is referred to as D_2, the major diameter.

Figure 5 shows the linear relationship between $\ln(E/E_{th})$ and D^2, according to Eq. 1. From Eq. 1, the one-dimensional optical diameter of the Gaussian beam can be determined when $D = D_0$, and consequently $E/E_{th} = e^2$. Considering the minor diameter, when $D_1 = D_{1,0}$ = 15.1 μm, E_1 equals 2.5 μJ. Now, calculating for D_2 at E_1 = 2.5 μJ yields D_2 = 16.8 μm. The cross-sectional area A of the focused elliptical laser beam is calculated as:

$$A = \left(\frac{\pi}{4}\right) D_1 D_2 \tag{3}$$

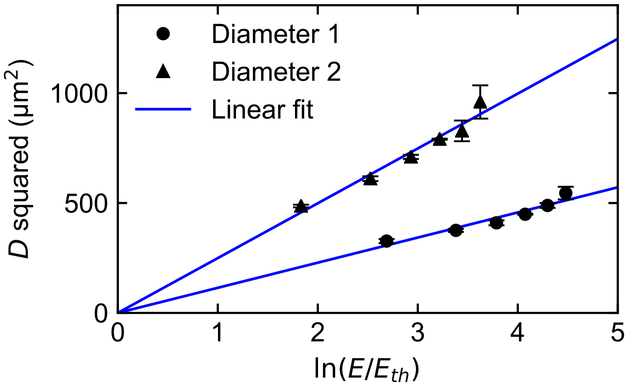

Figure 5. Linear relationship between $\ln\left(E/E_{th}\right)$ and D_2, according to Eq. 1.

Therefore, the elliptical area A is 1.99×10^{-6} cm^2. By knowing the focused laser beam area, the average fluence F can be calculated as:

$$F = \frac{E}{A} \tag{4}$$

and the peak fluence as:

$$F = \frac{2E}{A} \tag{5}$$

Thus, the threshold fluence of the tungsten substrate using the ~10 ps focused laser beam is 0.17 J/cm^2. This fluence threshold is similar to other values found in literature [12–15].

4 Conclusions

The one-dimensional spot size of the Gaussian beam at the waist was determined. The ablated spots were generated using single laser pulses focused on a tungsten substrate. The focused Gaussian beam generated ablative damage in an elliptical shape. Thus, the Gaussian beam was represented with a two-dimensional spatial distribution. The minor diameter of the elliptical fit of the ablated crater contour was used to determine the energy and fluence thresholds. Using picosecond pulses, the threshold energy of tungsten was found to be 0.34 µJ, and the cross-sectional area of the focused elliptical laser beam was determined as 1.99×10^{-6} cm^2. Thus, the threshold fluence was calculated to be 0.17 J/cm^2.

References

1. Winer, I.: A self-calibrating technique measuring laser beam intensity distributions. *Appl. Opt.*, vol. 5, 1966, pp. 1437–1439.

2. Mauck, M.: Knife-edge profiling of Q-switched Nd:YAG laser beam and waist. *Appl. Opt.*, vol. 18, 1979, pp. 599–600.
3. Liu, J.: Simple technique for measurements of pulsed Gaussian-beam spot sizes. *Opt. Lett.*, vol. 7, 1982, pp. 196–198.
4. Kiang, Y.; and Lang, R.: Measuring focused Gaussian beam spot sizes: A practical method. *Appl. Opt.*, vol. 22, 1983, pp. 1296–1297.
5. Krüger, J.; and Kautek, W.: Ultrashort pulse laser interaction with dielectrics and polymers. *Adv. Polym. Sci.*, vol. 168, 2004, pp. 247–289.
6. Lednev, V.; Pershin, S.; Obraztsova, E.; Kudryashov, S.; and Bunkin, A.: Single-shot and single-spot measurement of laser ablation threshold for carbon nanotubes. *J. Phys. D: Appl. Phys.*, vol. 46, 2013, p. 052002.
7. Rasband, W.: ImageJ. http://imagej.nih.gov/ij/, 1997–2016.
8. Roichman, Y.; Waldron, A.; Gardel, E.; and Grier, D.: Optical traps with geometric aberrations. *Appl. Opt.*, vol. 45, 2006, pp. 3425–3429.
9. Sun, H.: Laser diode beam basics. *A Practical Guide to Handling Laser Diode Beams*, Springer Netherlands, 2015, pp. 27–51.
10. Alda, J.: Laser and Gaussian beam propagation and transformation. *Encyclopedia of Optical and Photonic Engineering*, C. Hoffman and R. Driggers, eds., CRC Press, 2015, pp. 1–15.
11. Haskal, H.; and Rosen, A.: Power and focusing considerations for recording with a laser beam in the TEM_{00} mode. *Appl. Opt.*, vol. 10, 1971, pp. 1354–1358.
12. Preuss, S.; Demchuk, A.; and Stuke, M.: Sub-picosecond UV laser ablation of metals. *Appl. Phys. A*, vol. 61, 1995, pp. 33–37.
13. Byskov-Nielsen, J.; Savolainen, J.-M.; Christensen, M.; and Balling, P.: Ultrashort pulse laser ablation of copper, silver and tungsten: experimental data and two-temperature model simulations. *Appl. Phys. A*, vol. 103, 2011, pp. 447–453.
14. Sniaukasa, R.; and Raciukaitis, G.: Laser micro-cutting of thick tungsten sheets. Lasers in Manufacturing Conference, 2015.
15. Pfeifenberger, M.; Mangang, M.; Wurster, S.; Reiser, J.; Hohenwarter, A.; Pfleging, W.; Kiener, D.; and Pippan, R.: The use of femtosecond laser ablation as a novel tool for rapid micro-mechanical sample preparation. *Mater. Des.*, vol. 121, 2017, pp. 109–118.

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14. ABSTRACT

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