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THE INFLUENCE OF SPOT DIAMETER, FLUENCE AND WAVELENGTH OF THE NANOSECOND LASER PULSES ON THE ABLATION RATE OF ALUMINUM

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În această lucrare este investigată dependența ratei de ablație a aluminiului de diametrul spotului laser şi de fluența pulsurilor laser scurte (nonosecunde) pentru lungimi de undă din domeniile vizibil (VIS) şi infraroşu (IR). Rezultatele experimentale indică, pentru un flux de energie constant, o scădere liniară a ratei de ablație cu diametrul spotului laser, atât în VIS cât şi în IR. Săderea liniară a ratei de ablație cu diametrul spotului duce la o creştere invers proporțională a ratei de ablație cu rădăcina pătrată a fluenței laser. în plus, rezultatele experimentale indică o fluență de prag inferioară şi o eficiență mai mare a ratei de ablație în cazul utilizării de pulsuri din domeniul VIS în comparație cu cele din IR.

In this work we analyse the dependence of the ablation rate of aluminum on laser-spot diameter and laser fluence in visible (VIS) and infrared (IR) nanosecond-pulses irradiation regimes. Experimental results indicate that, for a constant flux of energy, the ablation rate decays linearly with increasing the laser spot diameter, both in VIS an IR regime. The linear decay of the ablation rate with spot diameter leads to the inverse-proportional increase of the ablation rate with square root of the laser fluence. Additionally, the results indicate lower threshold fluence and a much higher efficiency of the ablation in the case of using VIS pulses as compare to the IR pulses.

Keywords: ablation rate, laser fluence, spot diameter, laser wavelength

1. Introduction

The removal of material from a sample surface caused by the incidence of short and high intensity laser pulses is called *pulsed laser ablation* (PLA). Material removal efficiency under the action of laser pulses is described by the *ablation rate*, Δh, defined as the maximum layer thickness ablated per pulse. Laser ablation of metals is an important key in practical applications such as electronics, optoelectronics and micromechanics. Quality and aspect ratio of microstructures generated on metals surface by laser ablation depends on laser parameters such as fluence, spot diameter and wavelength[1,2,3].

The fluence of the laser beam at the irradiated surface is a major determinant of the ablation rate. Previous experimental work on the ablation of

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metals and semiconductors with nano-second laser pulses indicate that the laser ablation rate increases with laser fluence [1,2,4,5]. The increase is linear in the low fluences regime and logarithmic for high fluences regime.

The diameter of the laser spot on the material surface is another determinant of the ablation rate, as well as of the width of microstructures generated on the sample and of the dimensionality of the expanding plasma plume [1,2,4,5]. Most of the previous experiments with nanosecond pulses were carried only on semiconductors and dielectrics, indicating that the ablation rate decreases with increasing the spot size and becomes approximately constant above a saturation value of the spot diameter.

The ablation rate is also strongly dependent on the laser wavelength [1,4,5,6,7]. The experiments on metals and semiconductors indicate that the threshold fluence increases and the efficiency of the ablation decays with increasing the laser wavelength.

In this work we analyse experimentally the influence of the spot diameter, laser fluence, and laser wavelength on the ablation rate of metals (aluminum) in nanosecond-pulses regime. The aluminum plate (1 mm thickness) is clamped on a movable mechanical stage which enables the laser beam to be focused on the sample surface by using a fixed lens system. The laser beam diameter is approximated by the diameter of the crater that is drilled into the sample. The approximation holds due to the large value of the beam diameter as compare to the thermal length, which determines the heat to propagate mainly along the laser-beam direction within the irradiated material. The number of laser pulses used for drilling a crater is chosen so that the ablation rate is constant during each consecutive laser pulse [1,7].

The laser beam diameter on the sample's surface is increasingly varied by translating the sample from its initial focal position toward the incoming laser beam. This leads to the optimum condition for ablation by avoiding the loss of laser energy due to the air break-down in front of the sample.

The increases of the laser-beam diameter on the aluminum-plate's surface while the laser flux is constant determine the decay of the incident laser fluence. Thereby, we can analyse simultaneously the influence of the beam-diameter and of the laser fluence on the ablation rate. The experiments are carried out in two wavelength regimes (infrared and visible) analysing the influence of the wavelength on the ablation rate.

2. Experiment

The experimental setup is depicted in figure 1. The laser pulses are emitted by a 'Brilliant' Q-switched Nd-YAG laser system provided with a second harmonic module (SHM). Laser-pulse duration is 4.5 ns and the repetition rate of the pulses is 10 Hz. The aluminum sample (1 mm thickness) is clamped on a 3D movable mechanical stage (1 μm resolution) which enables the laser beam to be focused on the sample surface by using a fixed lens system.

Two wavelengths regimes are used. In the first case, 200 IR laser pulses (λ=1064nm, pulse energy E = 360 mJ) are focused on the sample's surface to produce a crater. The number of the incident laser pulses is chosen so that the ablation rate is constant during multi-pulses irradiation regardless of the spot diameter on the surface of the sample [1,6,7]. Thereby, the ablation rate is determined by dividing the depth of the crater, which is measured with a metallographic microscope, to the number of laser pulses.

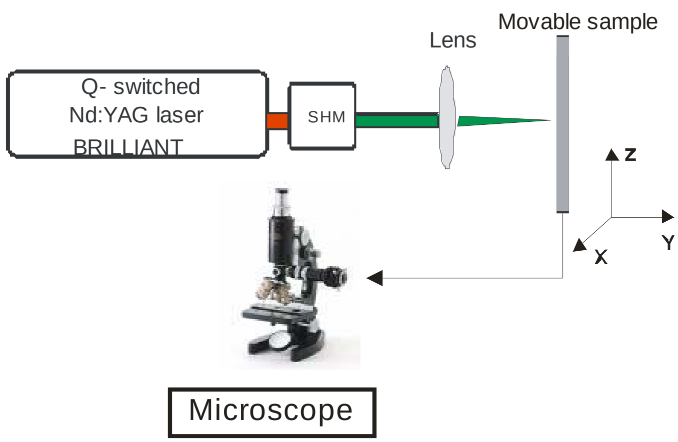


Fig. 1: Experimental setup for determining ablation rate of aluminium

For a certain position of the sample relative to the focusing lens we produce a series of 10 craters having the same diameter and depth. By measuring their diameter and depth we calculate the mean spot diameter and the corresponding mean ablation rate.

The increases of the laser-spot diameter and the corresponding decay of the laser fluence on the sample surface is realized by translating the sample 0.5 by 0.5 mm from the focus towards the focusing lens.

The second wavelength regime corresponds to the second harmonic (λ=532nm, pulse energy E = 180 mJ). In order to keep a constant ablation rate during multiple pulses irradiation we use 10 VIS pulses for drilling a crater with a certain laser spot diameter. The mean spot diameter and the corresponding ablation rate is the result of measurements on a series of 10 craters produced by maintaining the same relative position between the sample and the lens.

The increases of the laser-spot diameter and the corresponding decay of the laser fluence on the sample surface are realized by translating the sample 0.3 by 0.3 mm from the focus towards the focusing lens.

3. Results and discussions

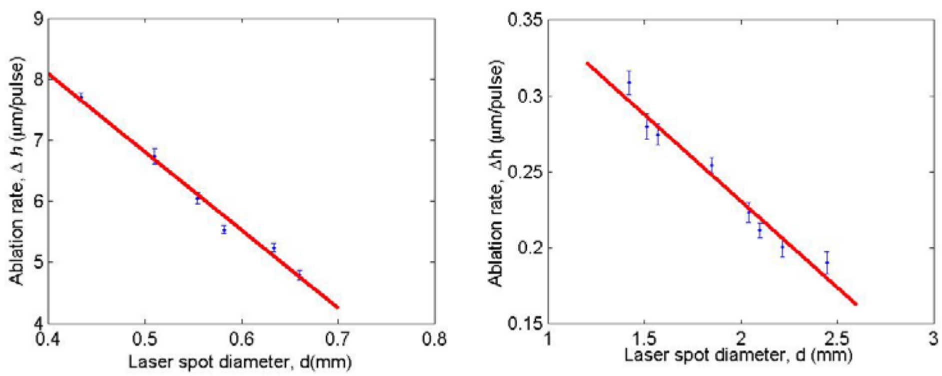
Fig. 2 presents the dependence of the ablation rate on the spot diameter while de energy flux of the pulses is constant (40 MW for the VIS pulses and 80 MW for the IR pulses). The graphs presented in figure 2a and 2b indicate that the ablation rate (Δh) decreases linearly with increasing the spot diameter (d) both in VIS and IR domains, respectively. The equations describing the fitting curves are

$$\Delta h = (13 - 12d) \cdot 10^{-3} \quad (\mu\text{m}) \tag{1}$$

for the VIS pulses and

$$\Delta h = (0.45 - 0.11d) \cdot 10^{-3} \quad (\mu\text{m}) \tag{2}$$

for the IR pulses.



(a) (b)

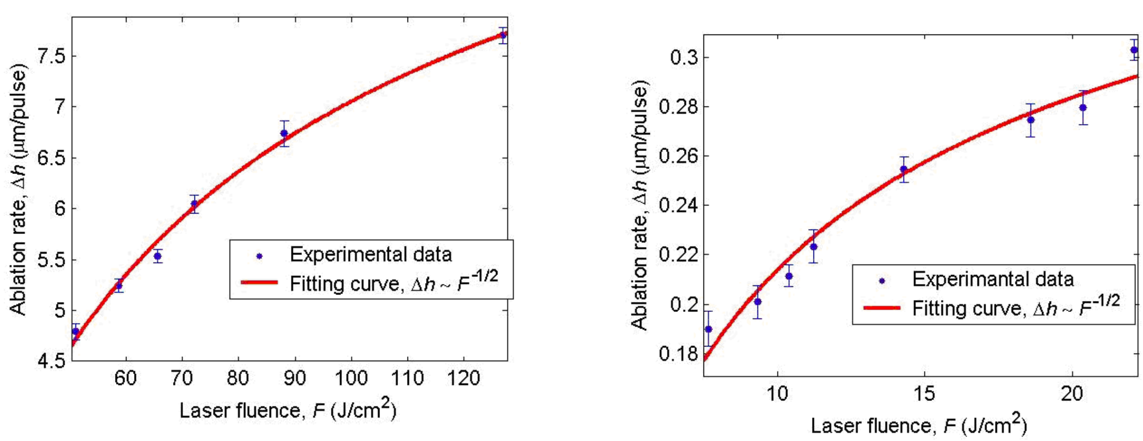
Fig. 2: Ablation rate of Al as a function of spot diameter for: a) E=180 mJ, λ= 532nm, b) E=360 mJ, λ= 1064nm. The duration of the laser pulse is 4.5 ns.

Equations (1) and (2) indicate that the decaying rate of Δh with d is much bigger (approximately $12 \cdot 10^{-3}$) in the case of VIS pulses as compare to the IR pulses ($\approx 0.11 \cdot 10^{-3}$). This denotes the VIS radiation is more appropriate for producing localized and well defined microstructures by laser ablation.

In the VIS domain (fig. 2a) we obtain a maximum ablation rate of 8 μm/pulse for a laser spot of 0.4 mm. In the IR domain (fig. 2b) we obtain a maximum ablation rate of 0.31 μm/pulse for a laser spot of 1.4 mm, while extrapolating the curve described by eq. (2) toward a 0.4 mm diameter we get an ablation rate of approximately 0.4 μm/pulse. The one order of magnitude higher value of the maximum ablation rate in the case of VIS pulses as compare to the IR pulses indicate that ablation efficiency is much higher in the case of VIS pulses. The very high efficiency of the visible pulses as compare to the infrared pulses is determined by the smaller reflectivity of the sample's surface and by smaller absorptivity of the laser-induced plasma plume in the visible range. Thereby, much energy of the visible laser pulses is coupled to the metallic target as compare to the IR pulses.

The linear decay of the ablation rate with the spot diameter in VIS and IR regimes is related to two phenomena. First, the increase of the spot-diameter determines a decay of the laser intensity. This further induces a decrease of the temperature rise at the surface of the irradiated sample, a decrease of the evaporation velocity and, consequently, a decay of the ablation rate with increasing the laser spot. Second, the smallest value of the spot-diameter that we use in the experiment (0.4 mm) is large as compare to the hydrodynamic-length of the plasma during the laser pulse ($\approx 10\,\mu$m). Thereby, the plasma plume expands one-dimensionally away from the sample and the attenuation of the incoming laser pulse within the plasma plume is related to the plume length. This further induces a linear character for the decay of the ablation rate with the spot diameter.

The increase of the spot diameter leads to a decay of the laser fluence at the target surface while maintaining a constant energy-flux of the laser pulses. Fig. 3 presents the dependence of the ablation rate on the laser fluence in VIS (Fig. 3a) and IR (Fig. 3b) regimes.



(a) (b)

Fig. 3: Ablation rate of Al as a function of laser fluence: a) λ= 532nm b) λ= 1064nm.

The equations describing the fitting curves indicate that the ablation rate increases with the laser fluence as $\Delta h \approx 1/\sqrt{F}$:

$$\Delta h = -58.5 / \sqrt{F(\mathrm{J/cm^2})} + 12.9 \quad (\mu m) \tag{3}$$

for the VIS pulses and

$$\Delta h = -0.8 / \sqrt{F(\mathrm{J/cm^2})} + 0.5 \quad (\mu m) \tag{4}$$

for the IR pulses.

By extrapolating the fitting curves toward a zero ablation rate we evaluate the ablation threshold fluence F_{th}. For example, for the IR pulses, the ablation threshold fluence is approximately 3 J/cm^2 (Fig. 4). For the visible pulses, the ablation threshold determined by employing the same method is about 0.8 J/cm^2, which is about one fourth of the IR ablation threshold. The decrease of the threshold-fluence with decreasing wavelengths originates in the increase of the intrinsic absorption of aluminum with decreasing laser wavelengths.

4. Conclusion

In this work we study experimentally the influence of the laser spot diameter and laser fluence on the ablation rate of aluminium irradiated with visible and infrared nano-second laser pulses. The experimental results indicate that the ablation rate decays linearly with increasing the spot diameter on the surface of the sample both in visible and infrared regimes. A maximum ablation rate of 8 μm/pulse is obtained for 0.4 mm spot diameter of the visible laser beam, while a maximum ablation rate of 0.31 μm/pulse is obtained by focusing the infrared laser beam to a spot with diameter of 1.4 mm.

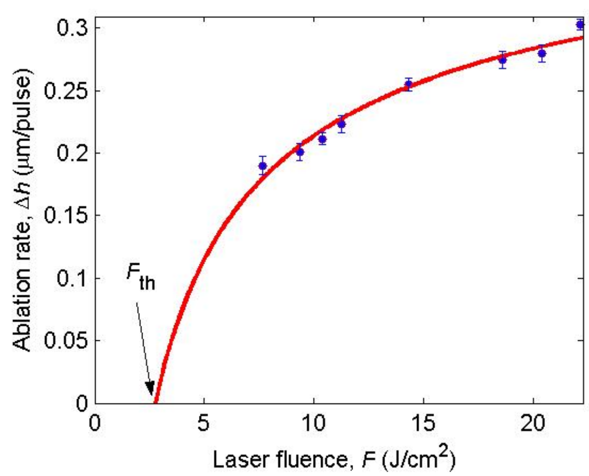


Fig. 4: Determination of the ablation threshold for an Al sample irradiated with infrared (1064 nm) ns laser pulses.

The linear dependence of the ablation rate on the laser spot diameter denotes a uniform attenuation of the incoming laser beam within the emerging plasma-plume that has a hydrodynamic length smaller than the laser spot diameter. Increasing the fluence of the incident laser beam leads to a marked increase of the ablation rate. The ablation threshold fluence is demonstrated to be approximately 1 J/cm^2 in the case of using visible pulses, which is four times smaller than in the case of infrared beam. This indicates that the visible radiation is more efficiently coupled in the metallic sample than the infrared radiation.

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