Influence of Femtosecond Laser Parameters on Metal Ablation Volume

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Abstract: Femtosecond laser ablation of stainless steel was studied. Two ablation regimes were identified. Analytical model of metal ablation volume calculation is proposed and confronted to experimental results. For desired microtexturing, the fluence and number of pulses are essential.
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1. Introduction

Over the past few decades, ultrashort pulsed lasers have been widely used in the micromachining and texturing fields, due to the ultrashort time scale and the ultrahigh laser intensity.

The laser matter ablation is controlled by the following parameters: material, laser beam characteristics and processing environment [1]. Another aspect of the process is the thermal diffusion distance of the laser energy around the impact area, which depends on the laser pulse duration and the thermal conductivity of the material. For high precision micro-machining, ultrashort laser pulses (10ps or less) are preferable [2].

In our study, the dependence of the volume of ablated metal with experimental conditions was shown, such as laser fluence and number of pulse in static laser shots. Three laser-matter interaction regimes were identified, two of which are ablation regimes. An analytical model of prediction of the metal ablation volume is proposed taking into account the material properties and the laser beam characteristics.

2. Backgrounds

For a Gaussian beam, the spatial fluence profile, F(r), is given by: $F(r) = F_0 \exp(-2r^2/w_0^2)$, where r – radius of the laser beam, F_0 – peak fluence, given by $F_0 = 2E/\pi w_0^2$, and w_0 – radius at $\frac{1}{e^2}$ of F_0 and E – the pulse energy.

In case of static shots, when fluence values are above the ablation threshold, crater appears by ablation process. It is characterized by the maximum diameter of the damaged zone (D) and the depth (h). Both depend on the peak fluence/ablation threshold fluence ratio and the efficient radius of the laser beam. The expression of D^2 is given by: $D^2 = 2w_0^2 ln \frac{F_0}{F_{th}(N)}$, where $F_{th}(N)$ is the ablation threshold fluence of N pulses [3]. It enables first the calculation of the slope corresponding to the radius of the laser beam w_0, and second the determination of the N-pulse ablation threshold $F_{th}(N)$ by the extrapolation of the linear fit to $D^2 = 0$. During the repetitive laser impact, accumulation of energy occurs in the material, which isn't completely dissipated. It causes an effect of incubation [4,5]. The relation between N-pulse and single pulse ablation threshold fluences, is given by: $F_{th}(N) = F_{th}(1)N^{\xi-1}$, where ξ is the coefficient of energy accumulation. It characterizes the degree of incubation.

3. Experimental details

Ti-sapphire laser source was used, which delivers energy of 0.5 mJ (wavelength 800 nm, repetition rate 5 kHz, pulse duration 130fs, linear beam polarization). The samples used were stainless steel grade 316L, R_a = 50 nm. The morphology of the surface and the volume of the ablated craters were scanned by SEM and optical 3D profilometer.

4. Results and discussion

A set of static laser shots were realized at different fluences and with various number of cumulated pulses. For F = 2 J/cm^2 (fig. 1), with increasing number of pulses, we observe the evolution of the ablation process: ripples (N =10), low ablation (N=50, 100) and high ablation (more than 100 pulses).

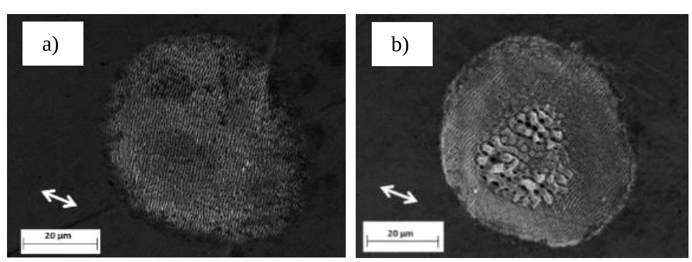

Fig. 1: SEM images of craters produced in stainless steel at F=2 J/cm^2
a) ripples for N=10, b) low ablaion for N=50

To investigate the incubation effect, the evolution of square of the crater diameter as a function of the fluence for N = 10, 20, 40 was plotted. By calculating the slope of the linear regression of the experimental results, the radius of the laser beam was deduced: $w_0 = 6.7 \pm 0.5$ µm. The extrapolation of the linear regressions allows to determine the values of the ablation threshold fluence $F_{th}(N)$. By plotting the logarithm of N· $F_{th}(N)$ vs the logarithm of N, we can determine the coefficient ξ from the slope of the linear relationship ($\xi = 0.83 \pm 0.05$ and $F_{th}(1) = 0.46 \pm 0.04$ J/cm^2). Finally, by combining the expressions shown in the background, we can predict the diameter of the laser impact as a function of the peak fluence and number of pulses, $D = w_0\sqrt{2\ln(\frac{F_0}{F_{th}(1)\,N^{\xi-1}})}$ (1).

Femtosecond laser ablation can be divided into two regimes: low or gentle ablation, governed by the Coulomb explosion $F_{th}^{\alpha} < F < F_{th}^{\lambda}$; and high or strong ablation, dominated by thermal vaporization $F_{th}^{\lambda} < F$. The F_{th}^{α} and the F_{th}^{λ} are respective ablation threshold fluences. For low regime, the ablation depth per pulse, h, can be described by: $h = \alpha^{-1}\, ln(\frac{F_0}{F_{th}^{\alpha}})$, where α is the absorption coefficient of the material [5]. For fluences less than 5 J/cm^2, a fit of the experimental data enables to calculate the slope and the intercept of the regression line leads to $\alpha^{-1} = 21 \pm 3$ nm and $F_{th}^{\alpha} = 0.56 \pm 0.04$ J/cm^2. For the high regime, the ablation rate depends on λ: electron heat diffusion length. In this case the ablation depth per pulse, h, is given by: $h = \lambda\, ln\left(\frac{F_0}{F_{th}^{\lambda}}\right)$. Identically, for fluences superior to 5 J/cm^2, the following values were determined: $\lambda \approx 160 \pm 15$ nm and $F_{th}^{\lambda} = 4.2 \pm 0.3$ J/cm^2.

In order to calculate the volume of ablated material (V) in the impact zone, the entire height of the crater was integrated in polar coordinates, substituting the expression of the ablation depth and diameter:

$$V = N\frac{\pi}{4}\alpha^{-1}w_0^2 ln^2\left(\frac{F_0}{F_{th}^{\alpha}(1)\,N^{\xi-1}}\right) \qquad (2)$$

Entering in a Matlab® model the laser source and optical system parameters (F_0, w_0, N) as well as the properties of the material (α^{-1}, $F_{th}(1)$, ξ) the values of the ablated volume were calculated.

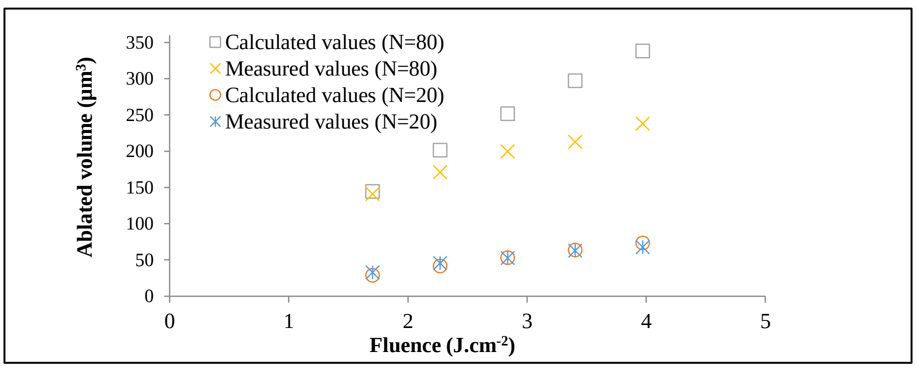

Fig. 2: Calculated and measured values of the ablated volume as a function of the laser fluence for N=20 and N=80

For N=20 measured values of the volume are in good agreement with calculated values, as shown on figure 2. However, for N= 80, a divergence is noticed. This is due to the accumulation of energy in the material. In this case, melting takes place, some of the liquid is ejected around the impact area, forming a burr and the other part re-solidifies in the ablation crater, which reduces the ablated volume. Therefore, the volume measured at N=80 is lower than calculated by the model, because it doesn't take into account the thermal effect.

To summarize the results above, we can conclude, that for pure ablation, without undesirable effects (burrs) we need to be in the low regime and adjust the fluence and the number of pulses.

5. References

[1] O. Varlamova et al, "Control parameters in pattern formation upon femtosecond laser ablation", Appl. Surf. Sci., 253, 7932-7936 (2007).

[2] S. Nolte et al, "Microstructuring with femtosecond lasers", Adv. Eng. Mater. **2** 23–27 (2000).

[3] J. M. Liu et al, "Simple technique for measurements of pulsed Gaussian-beam spot sizes", Opt. Lett. **7** 196-198 (1982).

[4] Y. Jee et al, "Laser-induced damage on single-crystal metal surfaces", JOSA B **5**, 648-659 (1988).

[5] P. T. Mannion et al, "The effect of damage accumulation behavior on ablation thresholds and damage morphology in ultrafast laser micro-machining of common metals in air", Appl. Surf. Sci., 233, 275–287 (2004).