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Simulation of ultrafast laser ablation topography of metals

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Abstract

It has been demonstrated in the past years that ultrafast lasers are excellent tools for materials micromachining. The ablation topology resulting by irradiation with these lasers depends on both the processing parameters and the material properties. The resulting thermal effects are negligible only if a good combination of processing parameters is chosen. Consequently, optimizing the processing parameters that lead to the required ablation dimensions and surface quality on a given material can be rather complex and time consuming. To enhance this parameters research, we developed the web-based tool LS-PLUME®, based on a numerical model that allows estimating the ablation profiles while preserving the surface quality. The simulated results were validated by comparison experimental ones and show that LS-PLUME® allows optimizing the micromachining process, both energy and time wise.

Keywords: femtosecond laser ablation; micromachining simulation; metals

1. Introduction

It has been already a few years that ultrafast lasers, namely femtosecond lasers, have been industrially applied as micromachining tools, as they allow texturing, drilling, cutting or milling surfaces with micrometric precision. Moreover, ultrafast laser micromachining can be performed with resulting negligible thermal damage, provided that the right processing parameters are chosen. The high quality of the ablation surfaces obtained by these lasers is mostly due to the nature of the interaction of these lasers with the material. The description of the physics of the interaction process is complex, and the ablation topography and surface

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quality resulting by irradiation with these lasers typically depend on several factors related both to the laser beam and the material properties.

When the surface of a material is irradiated with an ultrashort laser pulse, the energy is absorbed by free electrons due to inverse Bremsstrahlung. This is followed by thermalization of the electron subsystem, transfer of the electrons' energy to the lattice by electron-phonon coupling, and thermalization of the lattice or bulk. The evolution of the electron and the lattice temperatures is given by a system of coupled equations often referred to as two-temperature model. Eventually, depending on the laser energy density and the material characteristics, the resulting temperature gradients trigger thermal ablation, which may occur by vaporization, spallation, phase explosion or, more generally, combinations of these mechanisms (Zhigilei et al. 2009, Zhigilei et al., 2004, Colombier et al., 2012, Gamaly, 2011, Lorazo et al., 2003, Perez et al., 2003, Sokolowski et al., 1998). It is reasonable to assume though, regardless of the ablation mechanism, that the absorbed energy per unit volume decreases exponentially with the distance to the surface, yielding an ablation depth z that increases logarithmically with the absorbed fluence F (Momma et al., 1997, Audouard et al., 2017):

$$z_{abl}=\delta \ln \frac{F}{F_{th}} \tag{1}$$

where δ is the radiation penetration depth. Several additional factors have to be taken into account, namely (Cangueiro et al., 2017):

- When working with a laser beam with a Gaussian distribution of energy focused on the workpiece, the applied fluence F is not constant, but varies as a function of the distance to the focal plane and to the center of the beam;
- Part of this incident energy is reflected away due to the inherent surface reflectivity of the material R
- The ablation threshold fluence generally decreases with the number of applied pulses, due to incubation; We consider that the direction of ablation is parallel to the beam direction, which is not necessarily perpendicular to the material surface.

These criteria, added to Eq. 1, define how much of the applied fluence is converted into ablation, and can be used iteratively to simulate the ablation profiles resulting from laser scanning or laser precession, by considering the pulse repetition rate and laser movement parameters in relation to the workpiece (Fig. 1). This is the basis of the LS-PLUME®, the web-based application tool developed by Lasea, that enables a faster research of the optimal processing parameters for ultrafast laser micromachining.

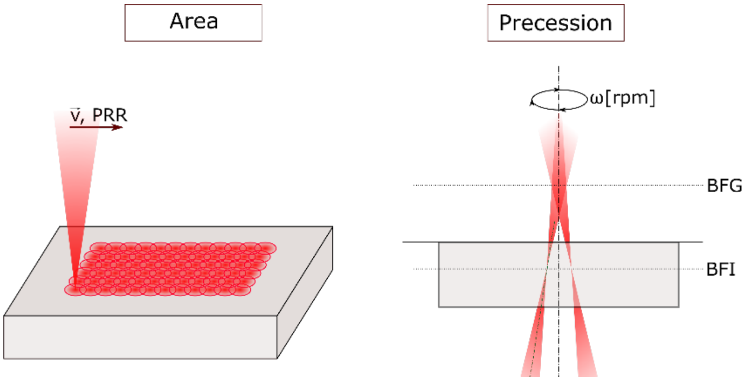

Fig. 1. Schematic illustration of the ablation strategies that can be simulated

2. Methods

The experiments performed in order to verify the model were carried out on polished samples of titanium, copper, tungsten carbide and stainless-steel. The tests were carried out in air using a Satsuma® HP2 femtosecond laser from Amplitude with pulse duration of about 330 fs, and 1030 nm radiation wavelength. The beam was focused at the surface of the samples using a 100 mm focal length telecentric lens. The morphological and topographical analysis of the treated samples was performed using a confocal optical microscope.

3. Results and discussion

The plots in Fig. 2 show the maximum depths obtained experimentally and by LS-PLUME for copper, titanium and tungsten carbide, as a function of the peak fluence and the scanning speed. In the calculations for simulating the ablation profiles, all the criteria mentioned above were considered. The simulated results are in quite good agreement with the experimental results within the limits of experimental error.

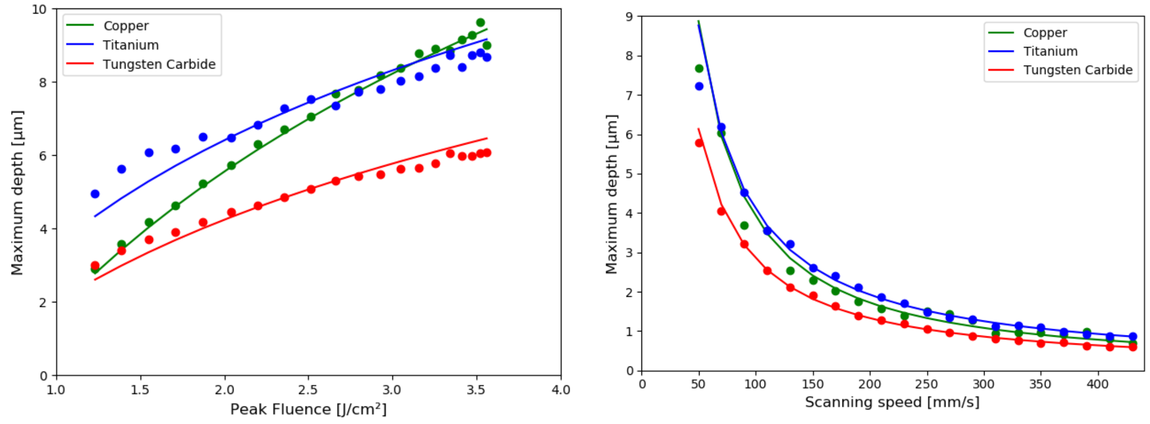

Fig. 2. Left: Simulated and experimental maximum ablation depths of laser tracks produced at 250 kHz and 50 mm/s scanning speed with increasing fluences on copper, titanium and tungsten carbide. Right: Simulated and experimental maximum ablation depths of laser tracks produced at 250 kHz and 3.3 J/cm² peak fluence with increasing scanning speeds on the same materials.

The experimental and simulated profiles depicted in Fig. 3 are of trench produced on stainless steel 316L with parallel lines distanced by 10 µm and scanned at 1 m/s at a repetition rate of 100 kHz, using 10 layers. The estimated ablation depth is in good agreement with the experimental results, as well as the taper angle at the edge of the trench.

The experimental and simulated profiles depicted in Fig. 4 are of cavity produced in a 100 µm thick stainless-steel sheet by precession. The micrograph on the left shows the cross section of the cavity with the simulated profile overlaid, which is also on the right. The hole was obtained using 11.9 J/cm² at 100 kHz, incidence angle of 4.5°, rotational speed of 30000 rpm and 50 ms of processing time. The model simulates well the ablation profile in what concerns both the entry and exit diameters, as well as the tapper angles.

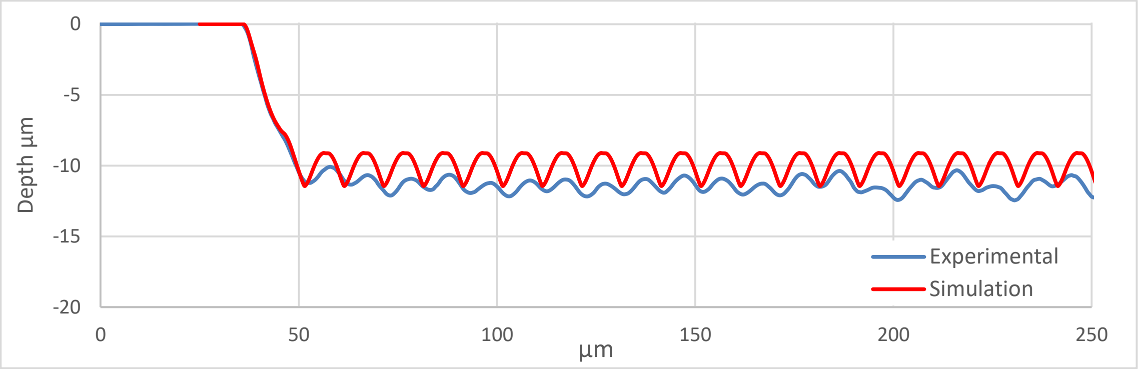

Fig. 3. Profile of area produced on stainless steel 316L, using 3.72 µJ (spot diameter of 22 µm), 1 m/s, 250 kHz, distance between parallel lines 10 µm and 50 layers.

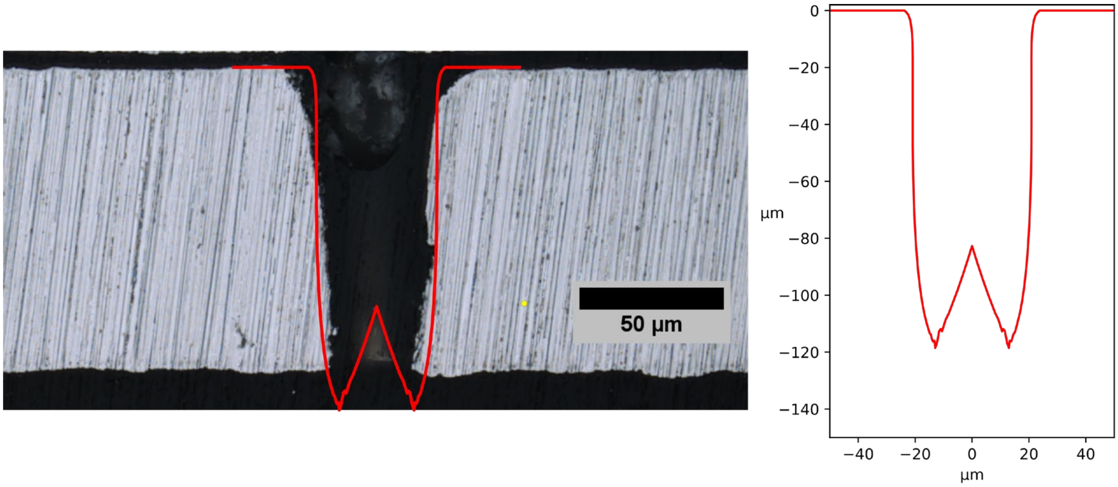

Fig. 4. Left : cross-sectional micrograph of a hole produced by precession on stainless-steel using 11.9 J/cm², 100 kHz, rotational speed of 30000 rpm and attack angle of 4.5°, the precession centre of rotation at the surface and the focal plane 400 µm under the surface. Right: corresponding simulated profile.

4. Conclusion

This works presents a tool that allows estimating the dimensions of ultrashort laser micromachined trenches and drilled cavities, taking into account the material properties and the processing parameters such as the pulse energy, repetition rate, scanning speed or tilting angle. The ablation profile simulations allow evaluating the effect of parameters such as the fluence, scanning speed or repetition rate has on the surface topography and properties, and if these comply with the required machined surface characteristics. The profiles of cavities drilled using the LS-Precess permit assessing the influence of the focus and center of rotation positions on the taper angles, depth attained and diameters of entrance and exit of the holes. The possibility of simulating this type of ablation profiles will certainly help on saving time and energy on the optimization of femtosecond micromachining processes.

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References

Zhigilei, L.V., Lin, Z. and Ivanov, D.S., 2009. Atomistic modeling of short pulse laser ablation of metals: connections between melting, spallation, and phase explosion. The Journal of Physical Chemistry C, 113(27), p. 11892-11906.

Zhigilei, L.V., Ivanov, D.S., Leveugle, E., Sadigh, B. and Bringa, E.M., 2004. Computer modeling of laser melting and spallation of metal targets. Proceedings of SPIE, 5448, p. 505-520.

Colombier, J.P., Combis, P., Audouard, E. and Stoian, R., 2012. Guiding heat in laser ablation of metals on ultrafast timescales: an adaptive modeling approach on aluminum. New Journal of Physics, 14(1), p. 013039.

Gamaly, E.G., 2011. The physics of ultra-short laser interaction with solids at non-relativistic intensities. Physics Reports, 508(4-5), p. 91-243.

Lorazo, P., Lewis, L.J. and Meunier, M., 2003. Short-pulse laser ablation of solids: from phase explosion to fragmentation. Physical review letters, 91(22), p. 225502.

Perez, D. and Lewis, L.J., 2003. Molecular-dynamics study of ablation of solids under femtosecond laser pulses. Physical review B, 67(18), p. 184102.

Sokolowski-Tinten, K., Bialkowski, J., Cavalleri, A., von der Linde, D., Oparin, A., Meyer-ter-Vehn, J. and Anisimov, S.I., 1998. Transient states of matter during short pulse laser ablation. Physical Review Letters, 81(1), p. 224.

Momma, C., Nolte, S., Chichkov, B.N., Alvensleben, F.V. and Tünnermann, A., 1997. Precise laser ablation with ultrashort pulses. Applied surface science, 109, p. 15-19.

Audouard, E. and Mottay, E., 2016. Engineering model for ultrafast laser microprocessing. Proceedings of SPIE, 9740, p. 974016-1.

Cangueiro, L., Audouard, E., Martin, P.E., Mottay, E., Ramos-de-Campos, J.A., Kupisiewicz, A. and Bruneel, D., 2018. Model for ultrafast laser micromachining. Proceedings of SPIE, 10520, p. 1052010.