Quantitative study of laser induced material removal mechanisms in aluminium: contributions due to vaporization, melt displacement and ejection.

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Abstract

We report the results of a threefold investigation of nanosecond laser ablation of aluminium that permits us to isolate the relative contributions to material removal associated with vaporization, melt displacement and melt ejection. The analytical methods employed and results will be discussed.

Laser micromachining has evolved into a mature technology and is now used in the fabrication of a wide range of miniature components and devices. Numerous diagnostic methods have been employed to elucidate the mechanisms underpinning material removal during laser ablation of metals, polymers and dielectric materials. Perhaps the most common of these include optical and electron microscopy, and profilometry to measure the crater dimensions and high speed imaging to analyse the characteristics of the laser plume.

Researchers have built up a complex picture of material removal in metals determined by mechanisms of vaporization, melt displacement and explosive melt expulsion. However, these studies, while delivering key insights into "pieces of the puzzle", do not offer detailed, quantitative insights into the interplay of these three mechanisms.

In this paper we report the results of a comprehensive study of nanosecond laser ablation of aluminium. In particular, we have undertaken a threefold strategy using profilometry, high speed imaging and recoil measurements using a ballistic pendulum that permits us to gauge the fluence thresholds and relative contributions of material removal due to vaporization, melt displacement and explosive melt expulsion.

The laser ablation source for all experiments was a copper laser master oscillator- power amplifier (MOPA) system providing single, 30ns pulses at combined wavelengths of 511nm and 578nm with pulse energies up to 1.3mJ. Details of this system are described in Coutts [1]. The output was focused onto polished aluminium targets at a focal spot size of 65μm.

The cross sections of the ablation craters were quantified using surface profilometry (Tencor Alpha Step 500). Both the total volume of the crater and the volume of displaced melt still present on the aluminium surface (ie. crater lip and surface dross) were calculated from this data.

The ballistic pendulum, used to measure recoil, is presented in detail in ref [2]. The whole apparatus, weighing ~0.3g, was placed in a vaccum chamber at <0.1mbar. The moment of inertia of the ballistic pendulum, I, the maximum displacement of the optical lever, Θ_{max}, the period of oscillation, T, and the distance of the site of ablation to the pivot point of the ballistic pendulum, L (in this case 2.5cm), for each experiment were used to determine the total recoil observed via Equation 1.

$$P_0 = 2\pi \cdot \frac{I}{TL}\Theta_{\max} \qquad (1)$$

The image analysis method for obtaining the volumes of molten droplets ejected from the sample surface with increasing fluence is fully detailed in [3]. These volumes, V, combined with the sample density, δ, droplet speed, s, and droplet ejection angle to the sample surface, ϕ, were used in Equation 2 to determine the total recoil momentum due to melt ejection.

$$P = \delta \cdot V \cdot s \cdot \sin(\phi) \qquad (2)$$

Recoil information was obtained under fluences ranging from 0-9.2 J cm^{-2}.

Studies of crater morphology as a function of increasing fluence show that at low fluences the irradiated region undergoes melting without any significant removal of material. At a moderate fluence of 3-4 $J.cm^{-2}$ melt displacement commences, typified by a ring of redeposited melt in the area immediately surrounding the crater. Measurements of the amount of displaced material

shows it saturates at ~2.5 x 10^{-9} cm^3 for fluences between 5 and 9 $J.cm^{-2}$.
At low fluences (<1Jcm^{-2}) there is no detectable recoil indicating either that the amount of material removed is negligible, or that some material removal may be occurring, but that the associated velocity perpendicular to the sample surface is negligible. Between fluences of ~1-12Jcm^{-2}, the recoil shows a linear increase with a slope (Recoil/Fluence) of ~9x10^{-9} N s cm^2/J. At fluences exceeding ~12Jcm^{-2} the measured recoil momentum was observed to saturate at a value of 1 x 10^{-7}Ns.

The high speed imaging analysis method was used to deconvolve the relative contributions to recoil velocity and mass due to ejected melt and vapour. This analysis showed that the recoil due to ejected liquid melt is negligible at low to moderate fluences between 0-8 $J.cm^{-2}$. At a threshold fluence of ~9 $J.cm^{-2}$ the liquid recoil momentum, as calculated from the high speed imaging data, rose to 10^{-10} Ns, a value that is 2 orders of magnitude smaller than that measured in the ballistic pendulum for the same fluence. This indicates that the vapour recoil almost exclusively dominates the total momentum observed in the ballistic pendulum experiment, with only ~1% contributed by the melt ejecta. This implies that the recoil data can be considered to be overwhelmingly representative of the vapour component that can be attributed with a threshold fluence of 1-2 Jcm^{-2}.

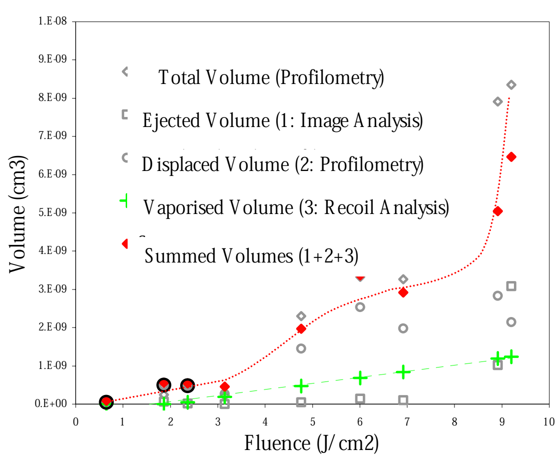

Figure 1: Volume of material removed due to the competing mechanisms of vaporisation, liquid melt displacement and explosive ejection. The sum of these results compare well with volume measurement calculated from profilometry.

Mele *et al* [4] reported that the velocity of vaporized material, for similar laser wavelength, pulse duration and fluence, experiences a transient high during during the 1st 200 ns of plume formation and becomes constant at a lower value of 3 x 10^4 ms^{-1} for timescales >1 μs. Using this value, which compares well with the integration time of the pendulum, we calculated the mass of material removed from the crater via vaporization from the measured recoil momentum. At the maximum fluence of 9 Jcm^{-2} investigated the volume of material removed was ~1.2 x 10^{-12} cm^3 corresponding to a mass of ~3.3 nanograms.

Figure 1 shows the individual contributions to laser induced material removal due to vaporisation, melt displacement and melt ejection, for fluences ranging from 0 to 9.2 $J.cm^{-2}$. Melt displacement accounts for ~60% of the total material removed at moderate fluences of 4-9 $J.cm^{-2}$, with the remainder being expelled as vapour. However, melt expulsion, which has a threshold fluence of ~9 $J.cm^{-2}$, is shown to dominate both melt displacement and vaporisation when it is present. In addition, the sum of these is shown to agree well with the removed volume calculated from profilometry measurements In this paper we will present details of this study and discuss the implications for high precision laser micromachining of aluminium and other metals.

The authors acknowledge the financial support of the Australian Research Council and EPSRC, UK.

1. D. W. Coutts, IEEE J. Quantum Electron., vol. 38, pp. 1217-1224, 2002.
2. D. Kapitan and D. W. Coutts, Europhys. Lett., vol. 57, pp. 205-211, 2002.
3. J.M. Fishburn, M. J. Withford, D. W. Coutts and J. A. Piper, vol. 43, pp. 6473-6476, 2004.
4. A. Mele, A. G. Guidoni, R. Kelly, C. Flamini and S. Orlando, Appl. Surf. Sic., vol. 109-110, pp. 584-590, 1997.