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Creating Controlled Features Underneath Metal Surfaces Through Laser-induced Melt Volume Expulsion

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Abstract

Laser-created sub-surface features inside transparent materials (e.g. glass) are used for crafting three-dimensional artworks and memorabilia that are displayed at home and offices. Creating sub-surface features in opaque metals by a laser beam was believed not feasible due to the high absorption coefficients of the metallic materials. Our previous report [1] for the first time demonstrated direct patterning in the sub-surface of stainless steel by realizing a series of microcavities to form a pre-designed pattern. In this paper, we report our latest study of the effect of laser pulse duration on microcavity formation. Results are presented for an austenite stainless steel plate interacting with single laser pulses with durations of 0.5 ms and 1 ms, using a Nd:YAG laser.

1 Introduction

Laser marking inside opaque metals has been reported recently [1]. During laser beam interaction with an opaque material, laser energy is absorbed at the surface and the optical penetration depth l_α is the reciprocal of the absorption coefficient α ($l_\alpha = 1/\alpha$). For stainless steel, α is $5.45\text{x}10^5$ /cm at 1064 nm [1], and the optical penetration depth is $1.8\text{x}10^{-6}$ cm. Most metals have similar optical penetration depths in the order of 10^{-6}-10^{-7} cm [1]. Therefore, direct sub-surface patterning beyond the optical penetration depth does not seem feasible. In our previous work, we demonstrated the formation of a controlled pattern in the sub-surface of a stainless steel plate with the sub-surface depth up to 790 microns [1]. In this paper, we aimed to further our understanding in the formation of the sub-surface patterns by looking into the effects of laser pulse duration and peak power density.

2. Experimental

A Lumonics JK 702H Nd:YAG laser delivering maximum energy of 3 J was used in our experiments. The focal length is 76.2 mm. To control the peak power density, the focal plane was set at different positions above the sample surface (Fig. 1). When the laser beam focal plane is on the sample surface, Z is zero. The radius of the laser beam spot on the metal surface and the peak power densities were altered by changing the Z values. Nitrogen (N_2) gas was introduced through a coaxial conical nozzle to minimise possible oxidation reactions. The gas pressure was controlled so as not to blow away the molten material. Commercial austenite stainless steel with thickness of 1 mm was used as test samples. The sub-surface microcavities were examined by optical microscopy and non-destructive computed topography (CT) scans. The sample preparation procedure was described in Fig. 2. When the ground surface came close to the laser melt spot, sandpaper with grit 800 was used and the ground surface was checked at every 40 seconds under an optical microscope. Only few microcavities were first observed at one side of the sample, e.g. the grinding surface was at the position of “a”. The grinding sandpaper with grits 1200 was used for finer control of material removal and the ground surface was checked at an interval of 20 seconds. More microcavities gradually appeared and sizes gradually increased with the prolonged grinding time. The grinding process stopped at the position of “b”, in which the sizes of the microcavities or melt pool are close to the maximum. The sectioned stainless steel samples were electrolytic etched in a mixture of oxalic acid (10 g) and H_2O (100 mL) at 6 V d.c. for approximately 30-40 seconds.

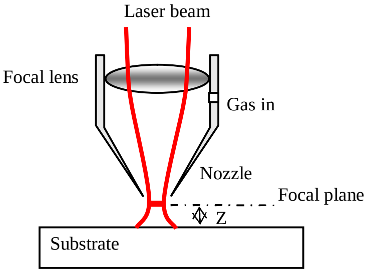

Fig.1 Experimental set-up

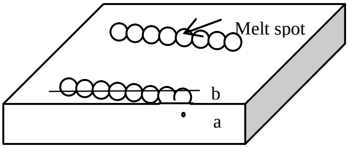

Fig.2 Illustration of X-sectional grinding process

3. Results and discussion

We found that subsurface microcavities existed where there were correspondingly circular micro-bumps on the sample surface. Figure 3 shows the longitudinal X-sectional CT scan images of the stainless steel. The lengths of the microcavities gradually decreased as Z increased for both samples at the pulse duration of 1 ms and 0.5 ms. For the 1 ms pulse, the length of the microcavities was shorter than that for the 0.5 ms pulse in all the experiments. Furthermore, when Z was high at 2.7 mm and 2.9 mm (i.e. lower peak power densities on the surface), microcavities nearly disappeared in the sample irradiated with the 1 ms pulse. In contrast, well defined microcavities were still observed in the case of the 0.5 ms pulse. This indicated that the formation of the subsurface microcavities was affected by both the peak power density and the pulse duration.

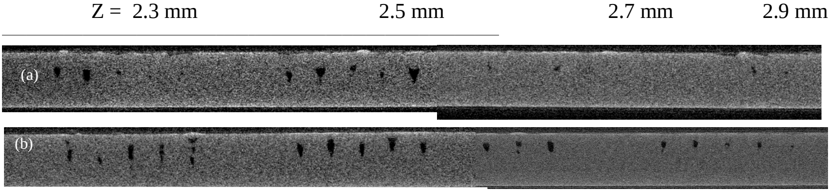

Fig. 3 X-sectional images of CT scans of microcavities in sub-surface of stainless steel with various Z values at (a) pulse duration 1 ms with pulse energy 0.82 J, (b) pulse duration 0.5 ms with pulse energy 0.43 J.

Figures 4a and 4b show the re-solidified melt pools with same peak power pulses. The pulses were separated 0.1 mm apart. The melt pools after the 1 ms pulse irradiation have rounded bottoms. Microcavities appeared at the bottom and middle of the melt pools. In the case of 0.5 ms pulse irradiation, the melt pools have sharply pointed bottoms. The length of the microcavities was longer. These results were repeated in several samples and were consistent with those shown in Fig. 3. Figure 4c shows a formed subsurface pattern “SIMTECH”.

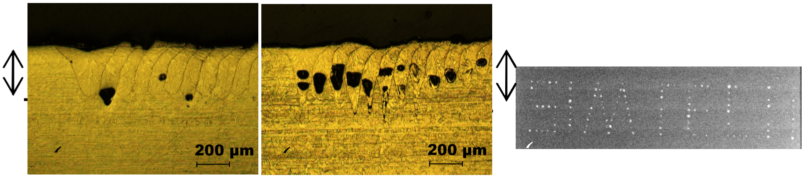

Fig. 4 Optical micrographs of stainless samples irradiated Z = 2.5 mm with laser parameters (a) X-sectional view with pulse duration 1 ms and pulse energy 0.8 J, (b) X-sectional view with pulse duration 0.5 ms and pulse energy 0.4 J, (c) X-ray top view of a subsurface pattern “SIMTECH” in steel

The absorbed laser energy caused localised melting. High peak power density causes increased flow of molten ejection and results in a crater on the metal surface.

Low peak power density tends to generate thicker melt layer with slow upward motion [5,6,7]. In our experimental conditions, the low peak power density resulted in incomplete ejection of the molten material after the laser pulse ended. The remaining melt material rapidly solidified and created a microcavity under the metal surface. The longer microcavities at the sub-surface resulted from the higher upward motion of the molten layers, which was due to the higher peak power densities. These results were consistent with those reported in reference, where degree of superheating showed almost a linear increase as the peak power increased. The upward motion speed of a molten layer induced by a shorter pulse is faster than the one induced by a longer pulse. Therefore, it was expected that the 1 ms pulse would generate deeper melt pool and longer microcavity in the sub-surface of metal because double energy was delivered to the metal with the double interaction time.

4. Conclusions

Effects of pulse duration on microcavity formation at metal sub-surface were investigated. Given the same laser peak power density, the 1 ms pulse generated wider and shallower melt pool, and shorter microcavity than those with the 0.5 ms pulse. The formation of the microcavity at sub-surface is determined by the degree of sub-surface superheating, which controls the hydrodynamics of the melt pool and is substantially influenced by the peak laser power density. The lengths of the microcavity obtained with the 1 ms pulse are shorter than those obtained by the 0.5 ms pulse.

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