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FEMTOSECOND LASER SINGLE PULSE AND PULSE TRAINS ABLATION OF COPPER

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ABSTRACT

The formation of nanostructures induced by femtosecond (fs) laser single pulse and pulse trains on copper (Cu) were systematically investigated. We found that the ablation size increases with the increasing of laser pulse number and laser fluence. A relative long interaction time is benefit for the formation of periodic surface structures when the laser fluence is determined. By using femtosecond laser direct writing on the surface of Cu, we obtained the optimum laser parameters to induce optimal ripple structures by using a pulse train. We found that the pulse train is more effective in controlling ripple's shape and quality compared with single pulse.

KEYWORDS

Femtosecond laser, surface structures, directing writing, pulse shaping

1. INTRODUCTION

Based on a study, laser-induced nanoscale metallic structures have been investigated extensively in the past due to their unique properties associated and excitation of localized surface plasmons [1,2]. Studies showed ultrashot laser pulses have proven to be a very promising tool for processing a variety of materials, especially the fs laser pulse [3-8]. Compared with long-pulse lasers, the fs laser offers the capability of non-thermal processing due to ultra-short pulse durations and ultra-high power densities, which makes it possible to limit the absorption region to the penetration of the optical pulse thus limiting the collateral damage and considerably increasing the fabrication precision and quality [9-11]. Besides, the very short duration may lead to the formation of plasma plume when the laser pulse is terminated and promotes the material into an extremely excited state followed by a rapid quenching [12]. So nanostructures with some special properties can be induced because of the interference of the incident laser with the surface plasmas.

Recently, the feasibility of electron dynamics control by shaping a fs pulse train has been theoretically proved by using first-principles calculations based on the time-dependent density functional theory. A shaped pulse train makes it possible to control electron dynamics, such as ionization, the distribution of electrons, electron density and electron temperature. The impacts of temporally shaped pulses on the morphology of metallic surfaces have been studies experimentally. Temporal pulse shaping can be advantageously used as a mean to control the periodic nanoripple's formation and thus the outcome of laser assisted nanofabrication Process. A researcher demonstrated a significant improvement of the micro structuring quality by adjusting the pulses separation is obtained and the processed surface appears to be smoother with better roughness.

In this work, the ablation size and morphology as a function of laser pulse number for various pulse energies were studied. We also investigated the advantages of shaped pulse train machining compared with conventional pulse. The related mechanisms for nanostructures formation and its potential applications were also discussed in our work.

2. EXPERIMENTAL SETUP

The schematic diagram of the experimental setup used in this work to machine samples is depicted in Figure 1. A Spectra Physics Spitfire regenerative amplifier producing 800nm, 35fs pulses at a repetition rate of 1 KHz with pulse energy up to ~ 3mJ was used. The fs laser pulse is linearly polarized. The energy of the laser pulses can be continuously adjusted by combining a half-wave plate with a polarizer. Several neutral density (ND) filters are used to further reduce the laser power in case of the power is too high, thus we can obtain any desirable values according to specific experimental conditions. The number of pulse bursts (irradiation time) is precisely controlled by using an electromechanical shutter. The fs laser pulse is temporally shaped to be a pulse train with an accurate pulse delay by a pulse shaper (BSI MIIPS BOX 640) and the energy pulse distribution of acquired pulse train is 1:1. The pulse trains used in the experiments consist of two sub-pulses and the pulse separations range from 0 to 5ps (a double pulse per train with 0 fs separation is actually a conventional pulse, that is a single pulse).

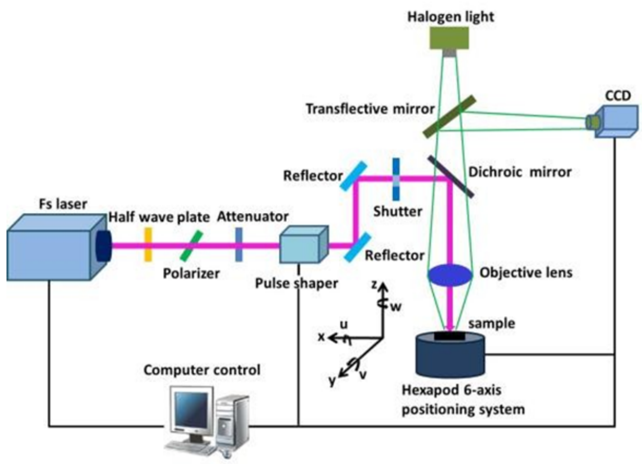

Figure 1: Schematic of experimental setup used for micromachining with shaped pulse trains.

The laser beam is directed into a plano-convex lens with a focal length of 100 mm and focused at a normal incidence onto the sample which mounted on a six-axis motion stage (M-840.5DG, PI, Inc.) with positioning accuracy of 1μm in the x and y direction and 0.5 μm in the z direction. The sample used in our experiments is Cu (10×10×1.0 mm, purity: 99.9%, polycrystalline) with single side mechanically polished. The ablation shapes and morphologies of the surface structures fabricated by single pulse and pulse trains are analyzed by a scanning electron microscope (SEM).

3. RESULTS AND DISCUSSION

Single pulse effects on fs laser ablation size of Cu were studied by varying the laser pulse number and laser energy fluence. Figure 2 shows the dependence of ablation size on the laser pulse number for various laser energy fluences. One can find that the ablation size gradually increases as the pulse number increasing when the laser energy fluence is determined, and finally the ablation size almost remains unchanged. As for this phenomenon, we explained as follows. It means that the interaction time of incident light with the Cu surface becomes longer when the laser pulse number increases. So the structures maybe formed in the initial several pulses. Once the structures are formed, the properties of the material may be changed. The ablation threshold can be decreased because of the structures formation. Thus for the subsequent pulses, the material can be ablated easily and enlarge the ablation size. Therefore, the ablation size increases with the increasing of laser pulse number. For the laser energy fluence effects, because the fs laser used in the experiment has a Gaussian spatial intensity profile. It implies that only the central incident light can induce ablation in the low fluence regime. When the laser fluence increases, the peripheral area of the incident light can also induced ablation. So the ablation size increases gradually.

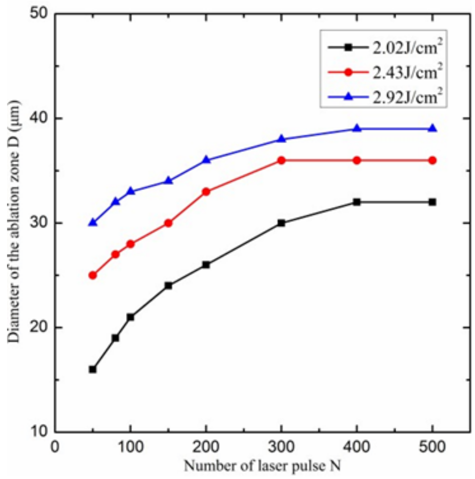

Figure 2: The ablation size is as a function of laser pulse number for various pulse energy fluences.

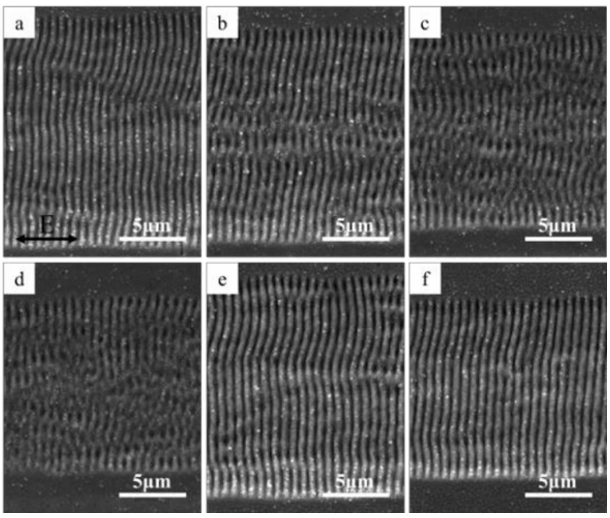

Figure 3: SEM images of morphologies on Cu surface induced by fs laser with a fluence of 4.68 J/cm2 and scan velocities of (a) 100 μm/s, (b) 200 μm/s, (c) 300 μm/s, and (d) 400 μm/s. (e) and (f) are induced by a pulse train (double pulses per train) with scan velocity 100μm/s and pulse separation of 50fs and 100fs, respectively. The double-headed arrow (E) represents the polarization vector of the laser beam.

We also study the effects of laser energy fluence, scan velocity and pulse separation (pulse train with double pulses per train) on the formation of periodic ripples induced by a fs laser pulse on Cu surface. On this basis, we obtain different ripple structures at different laser parameters as shown in Figures 3 and 4. Figure 3 shows the effects of scan velocity and pulse separation on the formation of periodic ripples with a laser energy fluence of 4.68 J/cm2. The ripple structures consist of an array of groove patterns with the period of (660±20) nm estimated by reading distances between two neighboring ripples in Figure 3 formed on the sample surface. All the ripples induced by scanning on the sample surface with femtosecond laser have an orientation perpendicular to the laser polarization vector which indicated with a double- headed arrow (E) in Figure 3(a). As Figure 3(a) and 3(b) show, clear and uniform ripple structures are formed for 100 μm/s while the ripple structures are a little obscure and slightly broken for 200 μm/s. For 300 μm/s and 400 μm/s, the ripple structures become more ambiguous but their longitudinal size become smaller.

The results show that the morphologies of induced ripple structures become fuzzy with the increasing of scan velocity when the laser fluence is determinated. We think the reasons for such phenomenon are mainly as follows: (1) Higher scan velocity can induce non-uniform laser energy deposition and accordingly lead to non-uniform ablation.

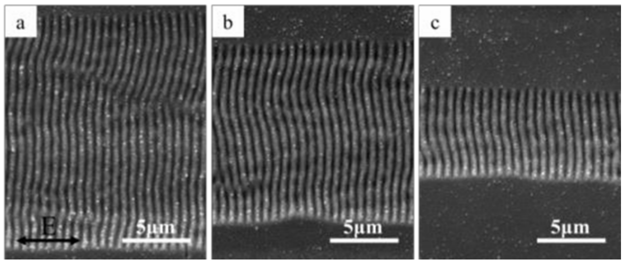

Figure 4: SEM images of morphologies on Cu surface induced by fs laser with scan velocity of 100μm/s and laser fluence of (a) 4.68 J/cm2, (b) 4.01 J/cm2, (c) is induced by a pulse train (double pulses per train) with laser fluence of 4.01 J/cm2 and pulse separation of 50 fs. The double-headed arrow (E) represents the polarization vector of the laser beam.

(2) In the higher scan velocity regime, the quantity of surface plasmon excited by scattered wave may become smaller and have a non-uniform distribution because the time of laser beam which interacts with sample surface becomes shorter. This may cause incontinuous interaction of incident laser light with excited surface plasmon polaritons. So the morphologies and quality of ripple structures are closely related to the laser scan velocity. This phenomenon has also been found on other material.

The effects of laser energy fluence and pulse separation with double pulses on the formation of ripple structures have also been investigated as shown in Figure 3(e) and 3(f) combine with Figure 4. Compared with Figures 4(a) and 4(b), one can find that the ripple structures are clear without broken and their size have also been reduced in Figure 4(b). The reason for such phenomenon may be that the laser beam intensity has a Gaussian spatial distribution whose intensity in the beam edge is lower, so the fluence in the beam edge may be lower than the ablation threshold and can't induce ablation when the laser fluence decrease to 4.01 J/cm2. It is obvious that the quality of ripple structures has been improved by controlling and adjusting the laser energy fluence.

The pulse train (double pulses per train at pulse energy distribution of 1:1) effects on fs laser ablation of Cu are investigated by adjusting pulse separation between sub-pulses in a train and laser fluence. Figures 3(e) and 3(f) depict pulse separation impacts on the morphologies of ripple structures. Compared with the pulse separation of 50 fs, the ripple structures become straighter and their sizes also become smaller when the pulse separation is 100 fs. Figures 4(b) and (c) show the difference between single pulse and pulse train effects on the formation of ripple structures. The quality of ripples structures has been distinctly enhanced and their width is reduced to 6.8 μm which is smaller than the spot size (9.76 μm) by using double pulses. So we have obtained the optimum laser parameters to induce optimal ripple structures by using a pulse train (double pulses per train), that is laser fluence of 4.01 J/cm2, scan velocity of 100 μm/s and pulse separation of 30 fs. We believe these high quality ripple structures may have a wide range of applications in plasmonics, photonics, biochemical sensing, optoelectronics, micro/nanofluidics, biomedicine, optofluidics and other areas.

4. CONCLUSIONS

In summary, we systematically investigated the formation of nanostructures induced by fs laser single pulse and pulse trains on Cu. We discussed the relationship between the ablation size and laser pulse number, laser energy fluence. The morphologies of induced ripple structures become fuzzy with the increasing of scan velocity and the reasons for this are as follows: (1) Higher scan velocity can induce non-uniform laser energy deposition and accordingly lead to non-uniform ablation. (2) Non-uniform distribution of surface plasmons may cause the incontinuous interaction of incident laser light with excited surface plasmon polaritons. High quality ripple structures were acquired with proper laser parameters, and it may be applied to plasmonics, photonics, biochemical sensing, optoelectronics, micro/nanofluidics, biomedicine, optofluidics and other areas.

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