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Full Length Article

Hole-like surface morphologies on the stainless steel surface through laser surface texturing underwater

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ABSTRACT

Laser-matter interaction in the liquid environment can produce some special structures on the target surface under certain conditions. In this paper, group micro holes have been fabricated on 304 stainless steel surfaces through laser surface texturing underwater with nanosecond laser. The effects of pulse duration, scanning speed, laser fluence and scanning times on the surface morphologies have been investigated. The surface morphologies have been characterized through scanning electron microscope (SEM) and confocal laser scanning microscope (CLSM). Energy dispersive spectrometer (EDS) has been used to analyze the chemical compositions within the holes. For further clarifying the forming mechanisms of micro holes, high-speed camera was used to monitor the texturing process. The main conclusions are as follows. The group micro holes were fabricated through the water jet interaction due to laser-induced bubble collapsing. The sizes of these micro holes can reach below 2 μm. Increasing laser pulse width, the sizes of holes will increase accordingly due to laser-induced bigger bubbles. Before the target surface is full of the micro holes, lower laser scanning speed, higher laser fluence and more scanning times produce more micro holes on the target surface. While after the hole number is saturated, further increasing laser fluence and scanning times, or decreasing laser scanning speed tend to deepen the holes or make their inner surfaces smoother due to the multiple impingement of water jet, rather than increase the number of the micro holes. With this method, group through holes with a diameter of a few microns have been successfully prepared on the 304 stainless steel foil. So besides surface texturing, this method also demonstrate another great potential application in the field of drilling ultra-small through holes.

1. Introduction

With the development of modern industry, it has been noted that surface morphology plays a very important role for the applications. By designing and manufacturing appropriate surface micro structures on the mechanical part, its tribological properties can be improved [1,2]. For solar cell, reasonable surface morphology is beneficial for improving both the efficiency of light absorption and the overall photoelectric conversion [3,4]. By processing glass, silicon, metal and so on, self-cleaning surfaces can be obtained [5,6]. For heat exchanger, its heat transfer performance also can be enhanced with appropriate surface texturing [7].Thus, how to fabricate the expected surface micro structures has attracted great attentions from both industry and academia. Laser processing is one of the important and suitable methods for obtaining the idealized or designed surface morphology.

There are developed researches for laser surface texturing in the air atmosphere at present. With the long-pulse laser, e.g. millisecond laser, some typical surface morphologies can be produced under the combined action of the recoil pressure produced by the vaporized material, liquid convection and the surface tension gradient within the molten pool [8,9]. For ultrafast laser processing, due to nanomelts, recoil pressure and the interference of the incident laser light with the excited surface plasmons, a variety of nanostructures can be obtained on the target surface by controlling laser fluence, pulse number and some other parameters [10]. The pulse duration and peak power density of the nanosecond (ns) laser are between those of the long pulse and the ultrashort pulse. So vaporization and melting coexist generally. For ns laser, single-pulse mode is usually applied to produce micro cavities and laser-scanning mode is used to produce the grooves [11].

In addition, the laser-matter interacting environment is also the main factor influencing the formation of the surface morphology. Due to the combined effects of the chemical corrosion and laser ablation, it

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can obtain totally different micro structures on silicon through laser texturing in SF_6 [12–14]. Luo et al. [15],who conducted an experiment about laser surface texturing on the stainless steel in the air, oxygen, nitrogen and argon, found that the oxygen environment was more likely to promote the growth of surface nanostructure.

When laser-matter interaction occurs in the liquid environment, the effect of liquid confinement, liquid cooling, and laser-induced cavitation processes will make the process more complex than that in the air, and accordingly the final results are significantly different. S Zhu et. al. studied laser ablation of Si in the water and ambient air. They observed that under certain conditions, nanosecond laser ablation rate underwater was higher than that in the air due to the water confinement effect [16,17]. Silvennoinen et. al. also obtained the similar conclusions when conducting femtosecond laser ablation under the sprayed thin water film [18]. About the influence of the liquid environment on the surface morphology, Sepehr Razi et. al. observed that a more uniformly patterned surface was obtained in the water because of the complex interaction between laser beam, water phase, created bubbles, confined ablated particles, melting, hydrodynamic instabilities and rapid quenching [19]. Trtica et. al. performed picosecond laser ablation on one spot of titanium surface in the water and air respectively. Spongy-like structures appeared on the surface underwater and the surface roughness obtained underwater was higher than that in the air [20]. Generally speaking, investigation of the surface modification by laser in the liquid phase is still a challenge. Until now many anomalous or novel phenomena have not been elucidated clearly due to lacking of direct experimental supports.

In this paper, we have performed the detailed study of 304 stainless steel surface structures through nanosecond laser scanning. Hole-like micro structures were observed on the target surface. The effects of laser parameters on this kind of structures were studied. The formation mechanism of the micro holes was investigated through metallographical characterization, component analysis and laser-induced bubble monitoring.

2. Experiment

The target used in the experiments was 304 stainless steel with the dimension $20\,mm \times 20\,mm \times 0.6\,mm$ (length × width × thickness). The target was polished to mirror surface before laser surface texturing experiment, and its material compositions (wt%) are shown in Table 1.

The laser applied for surface texturing is a MOPA fiber laser with the wavelength of 1064 nm. Its pulse width ranges from 4 ns to 200 ns, and the repetition rate varies from 1.6 kHz to 100 kHz. Its maximum scanning speed is 8000 mm/s, and the maximum power is 20 W. The laser uses scanning galvanometer as the output method. At the focal plane, the beam spot size is about 50 μm. Fig. 1 gives the schematic of the experimental setup.

The experiments were performed underwater, the target was completely immersed into water and its surface was 1.5 mm below the water level. During our experiments, the sample surfaces were all set at the focal plane. Laser scanning scheme is also shown in Fig. 1 and the hatch distances between the adjacent scanning lines were set as 10 μm. The laser fluence of the incident light was varied by changing laser power. Laser parameters used in the experiments are listed in Table 2.

After laser processing experiments, surface morphology was mainly observed by scanning electron microscope (SEM, Hitachi S-3400N). In order to quantitatively evaluate the influence of laser parameters on the micro-hole densities, SEM pictures were analyzed to count the number of the micro holes with one home-developed statistical computer program based on the difference of chromaticity value in the SEM picture. Confocal laser scanning microscope (CLSM, Keyence VK-X1000) was also used to obtain 3D surface morphology, especially the information about the micro-hole depth. Keyence VK-X1000 CLSM can give the maximum contour height of one surface region. For our experiment, this value manifests the level of the maximum hole depth. So for all textured surfaces, we use the corresponding maximum contour height to quantitatively evaluate the influences of the experimental parameters on the hole depth. To accurately characterize the maximum contour height of one region, we discrete it into four parts, obtain the maximum contour height of each part and then calculate the average maximum contour height of all parts with Keyence multifileanalyzer. EDS (EDAX) was applied for the surface composition analysis.

Table 1
Compositions of Sus304 stainless steel.

	C	Si	Mn	P	S	Cr	Ni	N
wt%	0.05	0.53	1.12	0.031	0.003	18.35	8.16	0.04

High-speed camera, Phantom V2512, was used to monitor the texturing process providing some experimental support for the formation mechanism of the hole-like surface morphology. The arrangement of the bubble monitoring equipment is also shown in Fig. 1 within the dot-dashed line box. The high-speed camera has the maximum frame rates up to 1×10^6 fps, the minimum inter-frame time of 1 μs and minimum pixel size of 28 μm.

3. Results and discussions

3.1. Hole-like surface morphology obtained through laser surface texturing underwater

During our experiments, we have observed that, under certain experimental conditions, especially with relatively low laser scanning speed and high laser fluence, large amount of micro holes can be fabricated on the target surface. Fig. 2 gives one typical result of our experiment. The laser pulse width is 5 ns, laser fluence is 7.33 J/cm^2 and laser scanning speed is 0.1 mm/s. Laser scanned the surface one time. Hole-like micro structures distribute on the surface uniformly. It is worthy to be noted that the hole diameters are only on the order of a few microns or even below 2 μm, nearly reaching the diffraction limit of 1064 nm laser, as shown in Fig. 2(b). Actually, some researchers also observed the similar phenomenon during laser processing in the water. Charee et al. [21] observed that the remarkable micro holes were apparent when laser ablating silicon in the still water. With KrF ns laser ablation underwater, Elaboudi et al. [22] obtained micro holes or even nano holes on the PET polymer surface. These researchers mentioned that the micro or nano holes may be due to the laser-induced bubble collapsing, but without deep investigation and direct support. So in this paper we will investigate this phenomenon in detail.

3.2. Influences of laser parameters on the hole-like surface texturing

(1) Pulse duration

Fig. 3 gives the SEM images of the surface morphologies obtained with laser pulse durations 5 ns and 100 ns. Laser fluences are about 7.33 J/cm^2 and 6.93 J/cm^2, respectively. The scanning speed is 0.1 mm/s. Laser scanning time is 1. It is obviously noted that the diameters of the micro holes obtained with 100 ns are about 8–12 μm, much bigger than those obtained with 5 ns, just about 1–2 μm. Fig. 4 gives their corresponding 3D profiles measured by CLSM. It is observed that the holes obtained with 100 ns laser are also statistically deeper than those of 5 ns laser. As we have introduced, we use the maximum contour height to quantitatively evaluate the influences of the experimental parameters on the hole depth. Fig. 4 gives the maximum contour height for 100 ns is about 52.8 μm, and that for 5 ns is about 27.3 μm.

(2) Scanning speed

Fig. 5 shows the effect of the scanning speed on the surface morphologies at laser pulse width 5 ns. Laser fluence is about 7.33 J/cm^2. The scanning speed ranges from 0.1 mm/s to 3 mm/s. Laser scanning time is 1. Hole-like structures were all obtained. For all