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Effects of electrolytes on fine structures fabricated by hybrid process with short-pulsed laser and electrochemical machining

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Abstract
Fine structures provide materials with physical phenomena including tribology, wettability and biocompatibility on the surfaces of materials, and many researchers have studied to fabricate such structures to produce the desired functionality. However, few processes can fabricate multiscale structures and control chemical composition of material surface. The hybrid process with a short-pulsed laser and electrochemical machining (ECM) is then proposed to fabricate multiscale structures effectively and to control chemical composition of material surface, since a short-pulsed laser can fabricate nanostructures called as LIPSS (laser induced periodic surface structures) and ECM is an elution and coating process. In this study, the effects of electrolytes on fabrication of multiscale structures on 304 stainless steel substrates by using the hybrid process with a short-pulsed laser and ECM were investigated experimentally. When the laser irradiation in electrolytes, thermal effects of electrolytes leaded low laser power for fabrication of LIPSS. In the case of $CuSO_4$ solutions, LIPSS with copper precipitation were fabricated by only laser irradiation in the solutions. In addition, the hybrid process with a short-pulsed laser and ECM fabricated LIPSS on the surface processed by ECM and improved the processing amount due to the increase of electric field intensity on the irradiated surface by the hybrid process. Also, effects of electrolytes on fabrication of fine structures with the proposed process were experimentally investigated, and this study demonstrated that the multiscale structures and chemical composition varied with electrolytes.

Keywords: short-pulsed laser, electrochemical machining, electrolyte, multiscale structures, chemical composition

1. Introduction

Friction reduction, control of wettability and improvement of bioaffinity have been demanded for various manufactures by fabricating fine structures on a material surface. A short-pulsed laser can fabricate nanostructures referred to as LIPSS (Laser induced periodic surface structures) through self-organization. However, fabrication of multiscale structures has been needed to provide higher functionalities with manufactures, and a short-pulsed laser is hard to create multiscale structures efficiently since LIPSS are fabricated at low laser fluence. The hybrid process with a short-pulsed laser and electrochemical machining (ECM) that can create microstructures with short processing time by induction of electric field and ionization was, then, proposed to fabricate micro/nanostructures with high efficiency by increasing electric field intensity.

This study aims to investigate the effects of concentration of electrolytes on the fabrication of LIPSS since conditions of LIPSS fabrication and geometry of LIPSS depend on the irradiation environment. Fundamental experiments were conducted on a stainless steel alloy surface with 15 wt% NaCl solution and 15 wt% $CuSO_4$ solution, and periodicity and height of LIPSS and depth of laser crater were measured and the results were compared with that under air, water, 5 wt% NaCl solution and 5 wt% $CuSO_4$ solution [1]. In addition, elemental analysis was conducted in order to investigate the effects of electrolytes. Besides, the hybrid process with a short-pulsed laser and ECM was conducted in NaCl solution to fabricate multiscale structures and to investigate processing characteristic.

2. Experimental setup

Figure 1 illustrates the schematic of the experimental setup. The short-pulsed laser with 20 ps pulse duration and 1064 nm wavelength having the Gaussian beam profile was used. The thickness of liquids was set to 3 mm, and the laser was irradiated parallel to the ground without scanning. Laser irradiation was conducted by changing environment, fluence and pulses. Laser irradiation experiments were conducted without ECM to investigate the effects of the environment on the fabrication of LIPSS, and hybrid process was conducted by laser irradiation and ECM which processes a 2 mm square area to investigate processing characteristic. The geometry of LIPSS and the depth of laser crater were measured, and elemental analysis was performed.

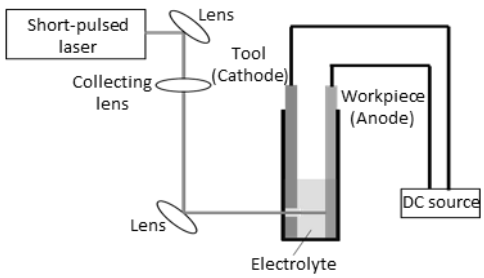


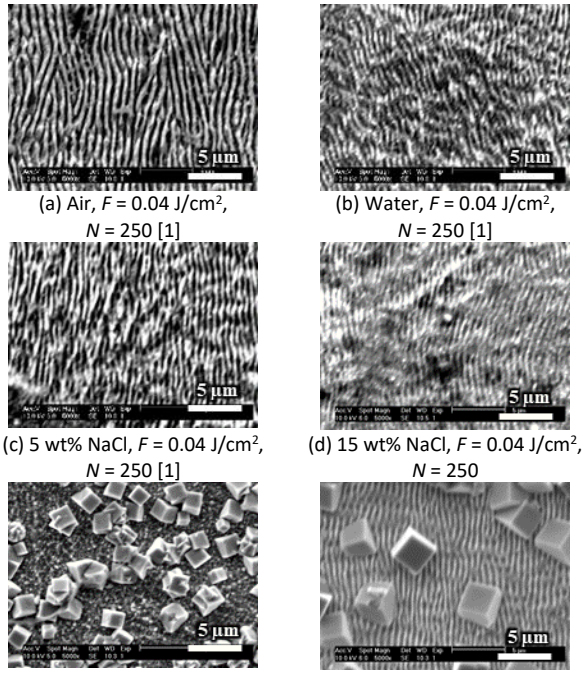
Figure 1. Schematic of experimental setup

3. Experimental results and discussion

Figure 2 shows the scanning electron microscope (SEM) images of irradiated areas under the air and the liquids. LIPSS

perpendicular to laser polarization are fabricated on the surface of crater under 15 wt% NaCl solution and 15 wt% $CuSO_4$ solution. In the case of $CuSO_4$ solution, LIPSS were fabricated only at high fluence under 15 wt% solution, though LIPSS were fabricated only at low fluence under 5 wt% solution since the attenuation rate increased rapidly with the increase of the concentration of the solution and high laser fluence was needed to fabricate LIPSS. In addition, larger particles were deposited on LIPSS than those under lower concentration of the solution, which were copper by analyzing with energy dispersive X-ray spectroscopy (EDX), since it is considered that the solution of higher concentration leads lager growth of copper particles. In liquids, laser irradiation with low fluence fabricated shallower LIPSS than LIPSS fabricated under the air, and the solution of high concentration decreased the height of LIPSS due to high attenuation of laser in liquids and solution of high concentration [2] as shown in Fig. 3. However, the deeper crater was created in 15 wt% NaCl solution than that under the air as shown in Fig. 4 since absorption coefficient increased by shortening wavelength and plasma expansion was suppressed in liquids inducing large ablation [3]. Depth of craters in solutions decreased with the increase of concentration due to high attenuation of laser [2] especially in $CuSO_4$ solution.

The periodicity of LIPSS fabricated in liquids was about 600 nm which was shorter than that of about 800 nm in the air



(a) Air, F = 0.04 J/cm^2, N = 250 [1]

(b) Water, F = 0.04 J/cm^2, N = 250 [1]

(c) 5 wt% NaCl, F = 0.04 J/cm^2, N = 250 [1]

(d) 15 wt% NaCl, F = 0.04 J/cm^2, N = 250

(e) 5 wt% $Cu(NO_3)_2$, F = 0.45 J/cm^2, N = 500 [1]

(f) 15 wt% $CuSO_4$, F = 0.45 J/cm^2, N = 500

Figure 2. SEM images of irradiated area in air and solutions with different fluence F and number of pulses N

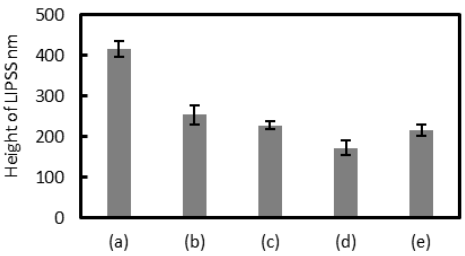


Figure 3. Height of LIPSS under (a) air, (b) water, (c) 5 wt% and (d) 15 wt% NaCl solution at F = 0.04 J/cm^2, N = 250 and (e) 15 wt% $CuSO_4$, solution at F = 0.45 J/cm^2, N = 500 [1]

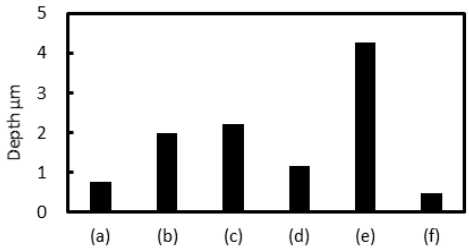


Figure 4. Depth of craters under (a) air, (b) water, (c) 5 wt% and (d) 15 wt% NaCl solution at F = 0.04 J/cm^2, N = 250 and (e) 5 wt% and (f) 15 wt% $CuSO_4$, solution at F = 0.45 J/cm^2, N = 500 [1]

since periodicity of LIPSS depends on the laser wavelength and is 0.50–0.85 times the laser wavelength [4] and solutions of high refractive index close to 1.333 of water shortened the laser wavelength.

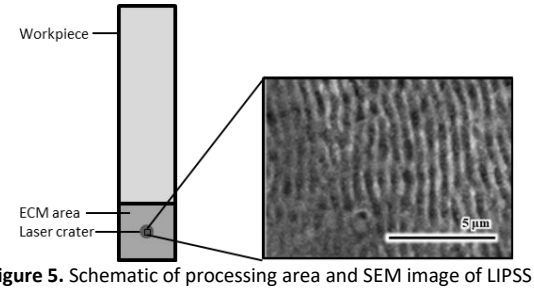


Figure 5. Schematic of processing area and SEM image of LIPSS fabricated with hybrid process

The hybrid process with a short-pulsed laser and ECM was conducted in NaCl solution, and the laser crater with LIPSS was created on the processed surface by ECM as shown in Fig. 5. The hybrid process created a deeper crater than the sum of crater depth created by laser irradiation and ECM depth. It is assumed that enhancement of electric field intensity and thermal effect improves processing amount. To determine the cause, this trend needs further study.

4. Conclusion

The effects of concentration of electrolytes on the fabrication of LIPSS on the stainless steel surface and processing characteristic of the hybrid process were investigated by using a short-pulsed laser and ECM with 15 wt% NaCl solution and 15 wt% $CuSO_4$ solution. From the experimental results, solutions of high concentration need high laser fluence to fabricate LIPSS, and decrease the height of LIPSS and the depth of crater due to high attenuation of laser. The hybrid process has a possibility to fabricate multiscale structures with high efficiency.

Acknowledgements

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