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Fabrication of durable hydrophobic micropatterns on stainless steel using a hybrid irradiation process

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ABSTRACT

Patterns were fabricated on AISI 304 stainless steel combining the wire electric-discharge machining (WEDM) with large pulsed electron beam (LPEB) irradiation to improve the surface hydrophobicity and corrosion resistance of the alloy. The WEDM-fabricated patterns showed a Wenzel-to-Cassie transition with contact angle (CA) of 140° at a groove depth of 250 μm, which indicated hydrophobic surface. LPEB irradiation of the WEDM-fabricated patterns increased the CA (166.7°) to the Cassie state at a lower groove depth of 200 μm. The LPEB-irradiated patterns had smooth surfaces that decreased the critical angle for Wenzel-to-Cassie transition. Attenuated total reflection-infrared spectroscopy revealed that hydrophilic functional groups on the surface were absent following LPEB irradiation. LPEB irradiation modified the surface corrosion resistance of a WEDM-fabricated pattern, likely because of a lower surface energy and formation of a passive resolidified layer following irradiation.

1. Introduction

Engineering stainless steels are widely used alloys because of their excellent structural properties, machinabilities and superior chemical stabilities such as corrosion resistance. Among the engineering stainless steels, the AISI 304 stainless steel (SS304) alloy was specially developed for better corrosion resistance compared with general steels; it was achieved by adding chromium. Because it has a strong resistance to chemical reactions, it is commonly used in pipes, cylinders, pumps, vessels, automobile parts and building materials. Although engineering stainless steels have relatively good corrosion resistance, they are nevertheless subject to pitting corrosion under highly humid conditions because of their high wettabilities [1,2].

Hydrophobic surfaces characteristic of certain metallic alloys have been intensively studied because of potential applications such as self-cleaning surfaces, for reduced liquid drag in pipes and microchannels, as the outer surface of vehicles, and for corrosion protection [3]. The fabrication of superhydrophobic surfaces has significantly advanced through the use of techniques including layer-by-layer deposition [4–6], electrochemical treatment [7–9], photolithography [10] and micro/nanofabrication processes [5,11,12]. The layer-by-layer deposition of hydrophobic materials on metallic alloys is one way to produce superhydrophobic surfaces. However, the bonding force between the hydrophobic film and metals is rather weak because polymers are used as the deposited materials. Electrochemical treatments can form hydrophobic functional groups on surfaces [13]; this is a suitable approach for products having complex surface shapes and textures that can tolerate liquid electrolytes. However, electrochemical treatments are generally useful only for polymers containing carbon or nitrogen chains that can lead to the formation of functional groups. Changing the geometrical shape of the surface using micro/nanofabrication methods has recently been used to impart superhydrophobicity to certain alloys. Micro/nano-pillars have been fabricated on a surface by laser ablation [5], wire-electric discharge machining (WEDM) [14], chemical etching [15] and micromachining [16]. Metals generally require post-processing, such as etching, to render their surfaces hydrophobic. Most of the post-processing techniques have used nonmetals to lower the surface energy, but delamination of the surface layer can lead to metal aging. Kwon et al. [5] fabricated nanostructures on SS304 and used electrodeposition as a post-processing technique. Liang et al. [15] fabricated a superhydrophobic magnesium alloy by chemical etching with stearic acid. Many studies have focused on providing hydrophobicity to patterned metals by lowering the surface energy by introducing other materials onto the surface. However, lowering the surface energy of patterned metals directly has not been adequately investigated.

Large pulsed electron beam (LPEB) treatment was introduced as a finishing process for metals and polymers many decades ago [17] and its effects on mechanical and chemical properties have been studied in the following decades [18–21]. LPEB irradiation can easily be applied to complex surface shapes and textures. Zou et al. [19] reported that LPEB treatment improved the hardness of SS316L and Kim et al. [18] have modified the corrosion resistance of KP1 and KP4 mold steels using this technique. LPEB irradiation has been used to increase the contact angles (CAs) of metallic alloys and decrease those of polymers [22,23]. Although the effects of LPEB irradiation on bulk metallic alloys have

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been examined, LPEB irradiation of micropatterns and its effect on hydrophobicity have yet to be evaluated. Also, the wettability mechanisms of metallic alloys are still obscure. In this study, LPEB was used to irradiate WEDM-fabricated SS304 patterns and their surface characteristics including morphology, hydrophobicity and chemical stability were investigated. The results indicated that using this fabrication method can generate a durable hydrophobic surface on the SS304 alloy and provide superior corrosion resistance and reduced surface roughness.

2. Experimental

2.1. Materials and methods

Micropatterns were fabricated with various groove depths (d) on standard AISI 304 stainless steel using WEDM (SL400G, Sodick Inc., Tokyo, Japan) (Fig. 1). The width (w) and pitch (p) of the patterns were fixed at 100 and 600 μm respectively. Brass wire of diameter 250 μm was used. The discharge voltage was set at 20 V and the wire feed rate was fixed at 30 mm/min; these were the optimized fabrication conditions to produce patterns without breaking the wire. The duty rate of the discharge process was 0.42 with 11 μs of pulse-on and 15 μs of pulse-off. The wire-feeding system continuously supplied new brass wire to minimize the shape error induced by tool wear. Patterns having various depths (50, 100, 150, 200 and 250 μm) were fabricated on SS304 sheet over an area of 20 × 20 mm^2 to investigate the effect of d on the wettability of the patterned surfaces. Three independent samples were fabricated for each depth. Water was used as the working fluid for the WEDM fabrication process.

2.2. LPEB irradiation

LPEB irradiation was performed on the WEDM-fabricated patterns using a high-current electron beam system (PF32A, Sodick). The experimental setup for the electron beam irradiation used an electron gun comprised of a cathode, anode and solenoid and an X–Y translation stage within a vacuum chamber. Argon gas was used as the plasma gas and its pressure was set to 0.05 Pa. The acceleration voltage was fixed at 30 kV. Electrons were accelerated between the cathode and anode, and the solenoid induced a Lorenz force that provided a helical pathway to the accelerated electrons. The helical pathway meant that the LPEB could be irradiated on the perpendicular surfaces of patterns without needing to tilt the stage or electron gun. Because the energy density of the LPEB followed a Gaussian distribution, the system was moved 20 mm following each pulse, providing 2 × 2 grids, to achieve a uniform energy transfer over the entire surface area. Thus, each irradiation cycle consisted of four pulses. Ten irradiation cycles were applied to each SS304 pattern.

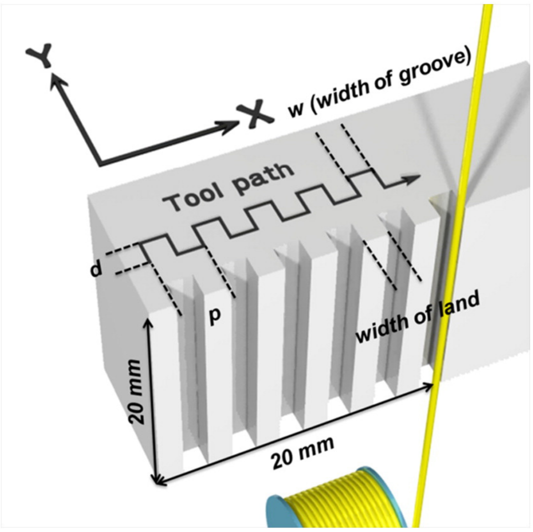

Fig. 1. Schematic diagram of wire electric-discharge machining (WEDM) and variables corresponding to pattern structures.

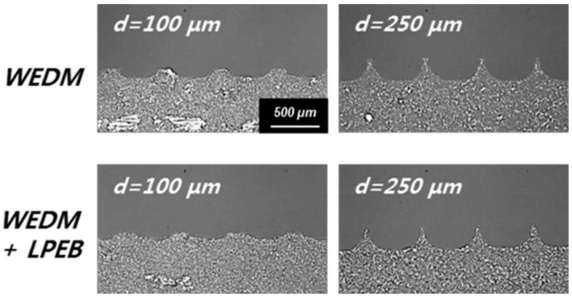

Fig. 2. Cross-sectional optical microscopy images of WEDM-fabricated patterns before and after large pulsed electron beam (LPEB) irradiation.

2.3. Characterization

The structural accuracy of the WEDM-fabricated patterns was evaluated using an optical microscope (OM; PIPHOT200, Nikon, Tokyo, Japan). Cross-sectional OM images were captured and the corresponding d and w values were determined. The CA was measured using the sessile drop method and a drop shape analyzer (DSA100; KRÜSS

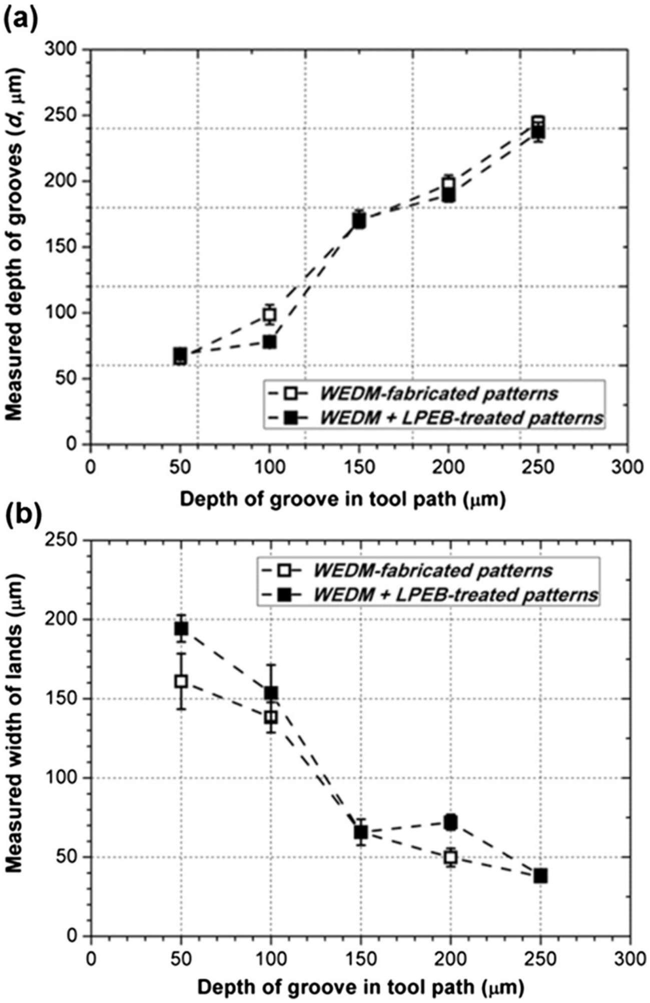

Fig. 3. Measured (a) groove depth, d and (b) land width of WEDM-fabricated patterns before and after LPEB irradiation as a function of tool path groove depth.