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One-step fabrication of superhydrophobic surfaces with different adhesion via laser processing

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ABSTRACT

In this study, we developed a simple, low-cost and convenient method to fabricate grid structures of different scales on the surface of 6061 aluminum alloy via laser processing. By changing the line spacing (50, 150, 250, 300 μm) during laser beam irradiation, different sizes of the square-shaped unprocessed surface areas and cross groove structures could be achieved. By adjusting the area ratio between the accumulative microstructure and the unprocessed surface, the adhesion of a water droplet to the surface could be varied from a state of low adhesion (line spacing of 50 or 150 μm) to a state of high adhesion (line spacing of 250 or 300 μm). The results indicated that different surface wettabilities could be obtained on aluminum alloy surfaces through the combination of a crisscross groove structure and unprocessed surface, which together formed a square groove structure. Corrugated protuberances, granular bumps and pit texture were formed on the groove structure. The surface showed excellent superhydrophobic properties. The contact angle was as high as 154.6° and the sliding angle was 6° for a line spacing of 150 μm. In this case, the low adhesion led to a rolling and self-cleaning behavior. For the larger line spacings, the wetting state of the water droplet indicated a high adhesion to the surface and a transition of the Cassie-Baxter state to the Wenzel state. Surfaces with high adhesion are of great significance for water collection and preservation. The approach presented in this study provides a facile, low-cost and efficient method to fabricate superhydrophobic surfaces on all types of metallic materials for commercial applications.

1. Introduction

In recent years, various hydrophobic surfaces [1–4] have been prepared via a large number of imitation and preparation processes and have attracted tremendous interest in fundamental research due to their unique properties, such as high wear-resistance [5,6], corrosion resistance [7–9], self-cleaning capability [10,11] and high/low adhesion [12–18]. A well-known hydrophobic surface in nature is the lotus leaf, which can be best described by the Chinese saying "Live in the silt but not imbrued". One of the key features of a typical superhydrophobic lotus leaf is its "self-cleaning" capability, i.e., the surface does not become contaminated by dust. This is mainly because micro-scale mastoid structures with a waxy substance and nano-scale structures are distributed on the surface of the lotus leaf.

With the continuous exploration of the special morphologies and properties of various animal skin and plant leaf surfaces in nature, new hydrophobic surfaces are being developed through imitation of the observed surface effects. Moreover, as these special surfaces are gradually explored, they are becoming more widely used in a variety of fields, including metal rust-proofing, biomedicine, oil/water separation and optics [19–23]. Materials with "self-cleaning" capability can be applied to the surface of buildings, automobile glass and glasses. Dust affects the appearance of tall buildings, which cannot be easily cleaned. Therefore, the development of hydrophobic, self-cleaning surfaces with low adhesion has great significance for production applications.

So far, many different methods have been adopted to fabricate superhydrophobic surfaces, including etching [24,25], mechanical processing [26,27], sol-gel method [28,29], chemical/electrochemical deposition [30,31] and laser processing [32–34], which have allowed the fabrication of micro/nano-scale hierarchical structures on a biological surface for solving practical application problems. For example, Qu et al. [35] were inspired by the skin of

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the gecko and fabricated a superfine polydimethylsiloxane fiber surface using inductively coupled plasma and a micro-casting model. By changing the diameter, spacing and height of the superfine fibers, a surface with self-cleaning capability, high adhesion and good mechanical properties could be obtained. Bhushan et al. [36] prepared single-stage and two-stage hierarchic adhesive structures using a template-based approach, and were able to obtain self-cleaning surfaces with either low adhesion or high adhesion by changing the density and diameter of the fibers. Barbastathis et al. [10] produced regularly arranged nanopore arrays via printing. The prepared superhydrophilic and superhydrophobic surfaces showed good mechanical properties, self-cleaning capability, anti-fog behavior and high transparency. Zhong et al. [37] fabricated a superhydrophobic surface having microgrooves and microholes array with high transparency and stable mechanical properties via a femtosecond laser ablated template. Jagdheesh et al. [38] fabricated micro channels and pillars by a nanosecond laser source on thin aluminum surface. These microstructures could be controlled to achieve a transition from hydrophilic to superhydrophobic surface in a short interval of time. Lai et al. [39] have used femtosecond laser writing to successfully create on-demand wetting patterns on superhydrophobic TiO_2 nanotube array (TNA) surfaces with extremely high wettability and adhesion contrast.

Aluminum and its alloys are widely studied and used because they are green engineering materials, easily recyclable, low cost, and generally show good oxidation resistance, electrical behavior and thermomechanical properties [40,41]. Thus, aluminum alloys are good choices for substrates. Moreover, the preparation methods mentioned above are too complex, cost-intensive, and not suitable for mass production. Laser processing is a simple, low-cost method and can be used in mass production for the preparation of superhydrophobic surfaces. In this study, we directly produced grid structures of different sizes and with different groove structures on aluminum alloy surfaces via laser processing and compared the wettability of the resulting surfaces. The results indicated the successful fabrication of excellent hydrophobic surfaces with self-cleaning capability, and either low adhesion or high adhesion.

2. Material and methods

2.1. Materials

The commercially available 6061 aluminum alloy with composition of 96.0 wt.% aluminum, 1.2 wt.% magnesium, 0.7 wt.% iron and 0.8 wt.% silicon was purchased from Changchun Aofeng Metal Co., Ltd., China. For the experiments, samples with dimensions of 15 mm × 10 mm × 2 mm were fabricated via high-speed wire cutting. For the contact angle measurements, deionized water was used and the volume of the test droplet was 4 μL. The chemicals used in this study, i.e., ethanol and acetone, were of analytical grade and purchased from Changchun Chemical Reagent Co., Ltd., China.

2.2. Sample preparation

First, the aluminum alloy samples were successively polished with #600, #800, #1000 and #1500 metallographic abrasive paper and ultrasonically cleaned in deionized water, acetone and ethanol. Then, the polished aluminum alloy sample was blow-dried prior to the laser processing. Second, the grid structure was produced on the sample surface via laser processing (HBS - GQ - 20) at a laser wave length of 1060 nm and an output power of 20 W, with a laser spot diameter of 40 μm, repetition rate of 100 kHz and pulse duration of 10 μs. The power and scanning speed of the laser were set at 50% and 500 mm/s, respectively. The range between adjoining laser scanning lines is denoted as line spacing in this study. Different line spacings were used, i.e., 50, 150, 250 and 300 μm. The scanning process was repeated two times for each sample. Finally, the aluminum alloy samples were ultrasonically cleaned and dried at 200 °C for 1.5 h prior to the measurements.

2.3. Characterization

The morphology of the laser-processed surface was analyzed by scanning electron microscopy (SEM; EM-30, COXEM, Korea). Three-dimensional (3D) profiles of the laser-processed surface were obtained through confocal laser scanning microscopy (LSCM; LSM 700, ZEISS, Germany). The contact angle was measured at ambient temperature using a contact angle measurement instrument (OCA15pro, Dataphysics, Germany) and SCA20 software by placing a 4 μL pure distilled water droplet onto the surface of the sample. Average contact angle for each sample was measured repeatedly for five times. The surface roughness of aluminum alloy was measured using a MarSurf LD120 roughness profiler. The elemental composition was determined by X-ray diffraction (XRD; Bruker D8 Discover, Germany) analysis in order to determine the phase composition of the sample surface.

3. Results and discussion

3.1. Composition

The XRD patterns obtained for the polished aluminum alloy surface and the laser-processed surfaces are compared in Fig. 1. We observed diffraction peaks of varying intensity at 2θ of 38.434, 44.733, 65.014, 78.137, and 82.340° (Fig.1a); 38.544, 44.621, 65.096, 78.286, and 82.398° (Fig. 1b); and 38.481, 44.714, 65.097, and 78.213° (Fig. 1c). The peaks for the two types of aluminum alloy surface are in good agreement with the standard diffraction pattern for aluminum (ICSD PDF No: 89-0437). From left to right, the diffraction peaks correspond to the (111), (200), (220), (311) and (222) aluminum crystal planes, respectively. Laser processing is one of the most important conditions for the patterning of crystals with a preferential growth orientation. The high energy and impact of the laser irradiation caused the increase in crystallinity which

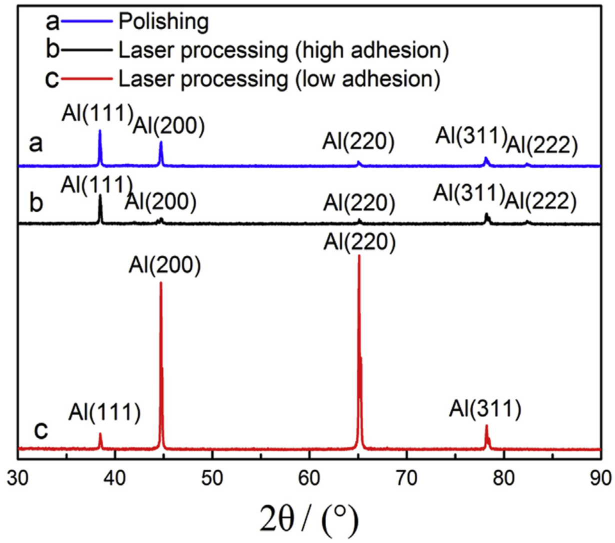

Fig. 1. Comparison of the XRD patterns obtained for: (a) The surface of the polished aluminum alloy. (b) The surface of a laser-processed sample (high adhesion). (c) The surface of a laser-processed sample (low adhesion).