Enhancing Water Harvesting Efficiency Using Laser-Ablated Brass Surfaces with Hybrid Hydrophilic/Superhydrophobic Patterns

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ABSTRACT-In recent years, global climate change and population growth have exacerbated freshwater shortages. To address this issue, harvesting water from atmospheric fog has emerged as a promising technique. Inspired by natural processes, the fabrication of hybrid hydrophilic (HI) and superhydrophobic (SHB) surfaces has gained significant attention for enhancing water harvesting efficiency. This study presents a simple and cost-effective laser ablation method for creating wettability contrast surfaces with triangular and parallel patterns on brass. Through X-ray diffraction (XRD) analysis and scanning electron microscopy (SEM), we investigated the structural and morphological effects on the wettability behavior of irradiated and non-irradiated brass. Additionally, we examined the influence of pattern shapes on water harvesting efficiency. Our findings indicate that triangular patterns significantly enhance water harvesting performance compared to parallel patterns.

KEYWORDS: brass, hydrophilic, hydrophobic, laser ablation, wettability, water harvesting.

I. INTRODUCTION

Water is known as a vital factor for human society and their activities. In recent years, lack of fresh water has been one of the intensive challenges around the world due to the fast industrialization, growing population, and global climate change [1]-[3]. Using the methods like filtration systems and desalination plants to solve the water crisis problem are often complicated and costly [4], [5]. Collection of small water droplets from atmospheric fog can be a good selection to overcome the water shortage problem [6]. According to the nature of water harvesting from fauna and flora, it was found that the capacity water harvesting depends on the various wetting patterns on their surface. The hybrid hydrophilic(HI)/-superhydrophobic(SHB) surfaces cause not only the effective adsorption of water droplet but also quick droplet removal [7]-[9]. Up to date, different techniques have been used to fabricate hybrid HI/HB surfaces namely chemical vapor deposition, soft lithography, dip coating strategy, UV irradiation treatment, hydrothermal, electrospinning, and laser ablation [10]-[15]. However, some of these methods suffer from high-cost process and low efficiency products and also they are often complicated and time consuming as well as requirement of multiple steps. Compared to the other methods, laser ablation technique is faster, easier, and cleaner. Moreover, this method is controllable and designable with adjusting laser parameters for fabricating micro/nanostructured surfaces with different wettability behavior [7], [10], [12]. The selection of suitable substrate material for laser ablation process is an important factor to achieving HI/HB surfaces. So far wetting behavior of brass with improving its properties have been attracted more attention in the industry [16], [17]. Some of potential applications for HB brass metal are in self-cleaning surfaces, oil/water separation, water

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harvesting from atmospheric fog, anti-icing, medical and microfluidic devices [10], [17], [18]. Assisted with laser ablation process, suitable brass surfaces with micro/nano structures containing nano-sized grains and nano-clusters of Cu_2O have been made with the aim of producing HB brass surfaces [16], [17]. In some related studies, various types of polymers such as iso-propyl acrylate (IPA) or thermal processes at high temperatures up to 300 ºC along with laser methods have been used to further improve the HB properties [16],[19]. In one research, brass metal has been deposited using laser ablation in the form of continuous and regular patterns on glass substrate to form a combination of HI and SHB structures for water collection from fog [10]. In this study, the regular parallel and triangular patterns with hybrid HI/SHB wettability were fabricated on the brass surface using laser ablation method in air environment as a green and low-cost method without the need for chemicals or extra materials. The structure and morphology of laser ablated brass was investigated with XRD test and SEM images, respectively. Furthermore, the aging effect on SHB behavior of irradiated tracks was investigated over time (60 days). The fabricated hybrid HI/SHB surfaces with parallel and triangular patterns was used in water harvesting test and their water collection efficiency from fog was compared with each other.

II. Experimental Setup

A. Fabrication of hydrophobic brass surface

At first, a brass foil with a thickness of 0.08 mm was prepared and it was cut into pieces with dimensions of 17 × 17 mm^2. Then, these brass samples were washed with distilled water using ultrasonic device for 15 min. One of these samples was as reference sample and the others were selected for applying the laser ablation process in an air environment on their surface with the dimensions of 15 × 15 mm^2. The brass surfaces were irradiated using a fiber laser (RFL-P30Q) with a wavelength of 1064 nm, a pulse width of 100 ns, scanning speed of 1800 mm/s, and a repetition rate of 20 KHz. The ablated process was carried out by keeping the laser parameters constant and changing the laser power of 9, 15 and 21 W on different three brass samples. B0 was named as pristine brass sample without any laser processes and B1, B2, and B3 were corresponded to the ablated samples with the laser power of 9, 15 and 21 W, respectively. The optical images of the ablated samples are given in Fig. 1. According to these images, the color of the samples changed after irradiation process, probably due to the creation of new structures and morphological changes in different laser powers.

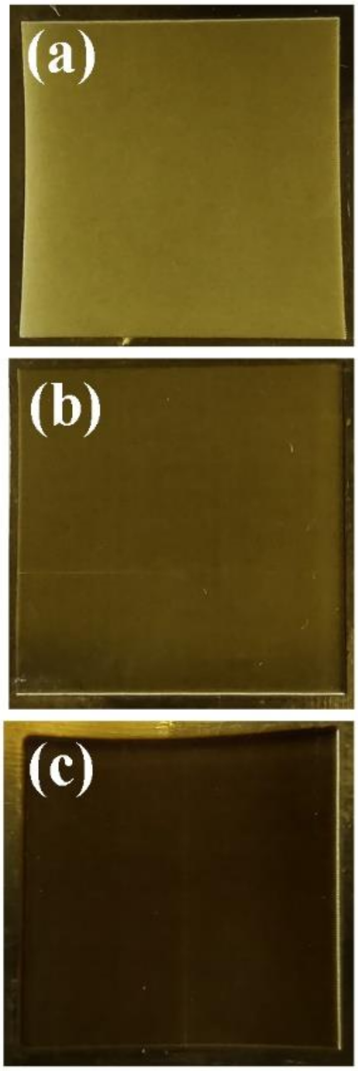

Fig. 1. Optical images of irradiated brass surfaces (a) B1, (b) B2, and (c) B3.

B. Water harvesting test

In order to fabricate hybrid HI/SHB surfaces, two different arrays of parallel line and triangular patterns was selectively inscribed on the brass substrates with size of 3×3 cm^2 at the same laser condition of sample B1. As seen in

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Fig. 2, the parallel pattern has HB tracks with a diameter of 2 mm and 2 mm distance from each other. The triangular patterns consist of some HB triangles with the base and height size of 2 mm and 10 mm, respectively, as well as with the base edge-to-edge spacing of 2 mm. These prepared samples were used in water harvesting test. In the water harvesting experiment, the sample slides were fixed with a holder at 5 cm far from humidifier nozzle and then exposed to fog flow (~280 ml/h, relative humidity of 95%) generated using an ultrasonic humidifier (PH-402–27). The mass of water droplets falling by gravity force was measured with an electronic balance with an accuracy of ± 0.001 g as a function of time. The water harvesting rate (r) was calculated using the following equation:

$$r = m/At \tag{1}$$

where m is the mass of harvested water, A is the capturing area, and t is the time.

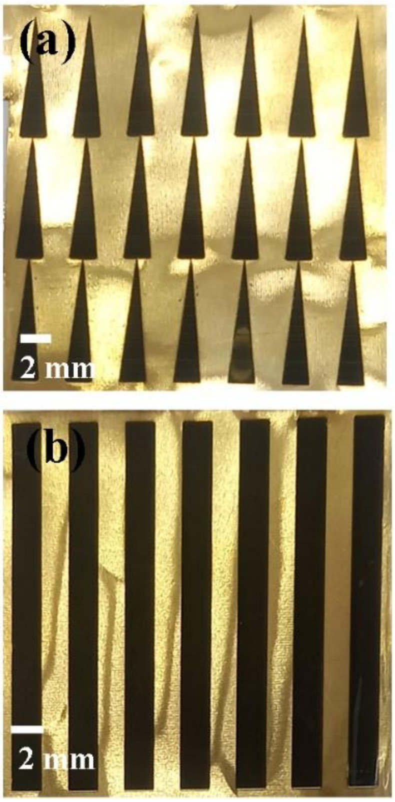

Fig. 2. The optical images of fabricated (a) triangular and (b) line parallel patterns on brass foil.

III. Results and discussion

Reference brass (B0) and B1 as ablated sample with the lower laser irradiation power were selected for XRD characterization and their results are given in Fig. 3. Fig. 3(a) and (b) relate to the XRD patterns of B0 and B1, respectively. As seen in both XRD patterns, one peak at the position of 42.4° corresponds to CuZn and the three peaks located at 49.5°, 72.3° and 88.0° were correspond to Cu [10]. After the laser ablation, four sharp peaks appeared at about 43.7°, 46.3°, 63.9°, and 80.2° in the XRD pattern of sample B1. Two peaks at 46.3° and 80.2° attributed to fabrication of CuO structure (ICDD Card 00-002-1041) and the two other peaks at 43.7° and 63.9° indicated the formation of Cu_2O structure on the frontal surface of the exposed brass which were matched with the ICDD Card 00-002-1041. Hence, the results of the XRD test confirmed the formation of copper oxide on the brass metal after performing the laser ablation process. It should be mentioned that the peaks at 43.7° and 46.3° are also overlapping with CuZn-ICDD Card 00-008-0349. Laser ablation process starts by applying laser irradiating on the brass target surface in an air environment that contains oxygen (O_2). With increasing the temperature of the target by the laser beam up to its melting temperature, the irradiated area melts and after the evaporation process, the plasma plume including atoms and ions of brass metal (such as Zn and Cu) and the O from air forms on the top of the irradiated region [12], [20]. The high pressure and temperature of plasma plume and the interaction of plasma plume species with the laser beam cause the ionization and separation of oxygen molecules which can be absorbed by the molten brass surface [12], [16], [17], [20]. Hence, the chance of Cu oxide structure formation is strongly increased and new material deposited on the brass surface as a solid material [12], [20].

The SEM images of the irradiated surfaces (B1, B2, and B3) are given in Fig. 4(a-c), respectively. In all images, the effects of laser ablation and porous structure of samples can be seen well leading to a change in the samples' roughness [12]. Moreover, it can be understood that due to the different laser irradiated powers, the morphology of the ablated surfaces is slightly different.

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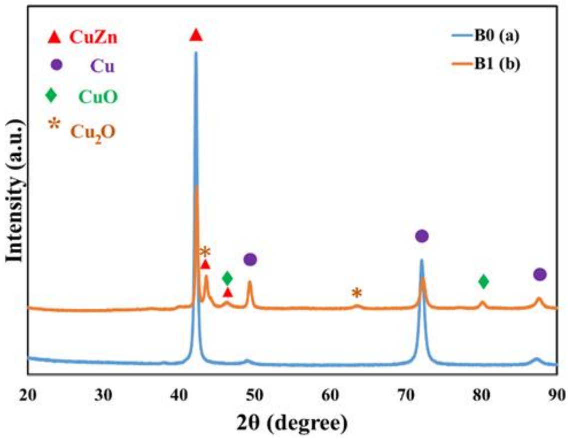

Fig. 3. XRD pattern of (a) brass and (b) laser ablated brass in air environment.

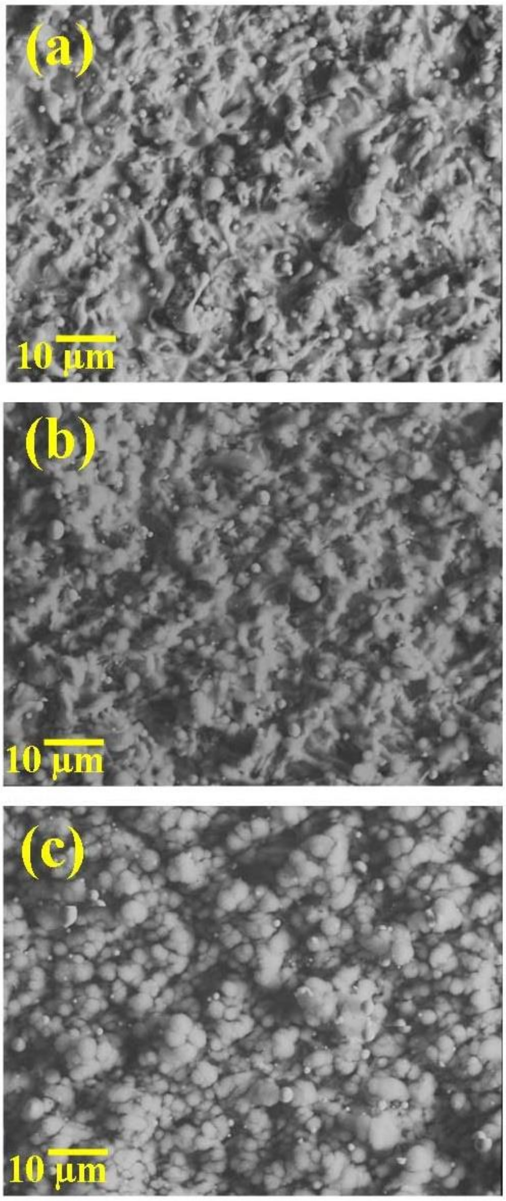

Fig. 4. SEM images of irradiated brass surfaces: (a) B1, (b) B2, and (C) B3.

The wettability of the samples (B0-B3) was investigated by measuring the water contact angle (WCA). Before the laser ablation process, the brass surface had a WCA of about 58°, which shows its HI behavior. Immediately after laser irradiation, WCA of all samples decreased such that the water droplet completely spread on the irradiated area and became SHB. The surface wettability of solid materials is largely influenced by factors such as surface structure, roughness, as well as surface chemistry changes [12], [21]. Oxidation of the surface increases the surface energy, which leads to the adhesion of water throughout the irradiated surface and causes the SHB behavior [12], [21]. In our method, the morphology of the irradiated samples changed by scanning the laser beam on the brass surfaces. On the other side, due to the formation of oxide structures which was confirmed by the XRD test, the surface of samples B1-B3 became suprhydrophilic (SHI) immediately after performing laser process. In order to investigating the aging effect on the surface wettability, the samples (B0-B3) were kept in the room environment and their wettability was studied at various time intervals of 10, 20, 30 and 40 days. There was no change in the surface wettability of the reference sample (B0), but all irradiated samples showed the SHB behavior over time. Among these samples, the B1 which was irradiated under the lower laser power selected to report the wettability test. For B1 sample, at time intervals of 10, 20, 30, and 40 dyes, the WCA reached about 30°, 69°, 97°, and 138° respectively (Fig. 5).

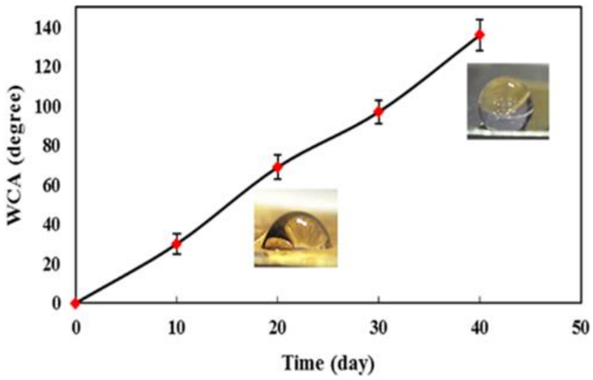

Fig. 5. Variation in WCA of B1 through aging effect.

It should be noted that after about 60 days, the irradiated samples couldn't hold the drop water

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on their surfaces as given in Fig. 6. Therefore, the surface wettability of irradiated samples changed from SHI to SHB with aging effect. The morphology of samples don't change over time, so another factor caused the HB behavior of the samples. According to the literature [12, 21], the carbon compounds in the atmosphere are absorbed by the laser-treatment surfaces over time, and these accumulation of carbon by airborne organic compounds' adsorption prevent the spreading water on the irradiated surfaces leading to HB behavior. B1 showed a little more hydrophobicity probably due to the morphological difference that led to more adsorption of carbon compounds on its surface.

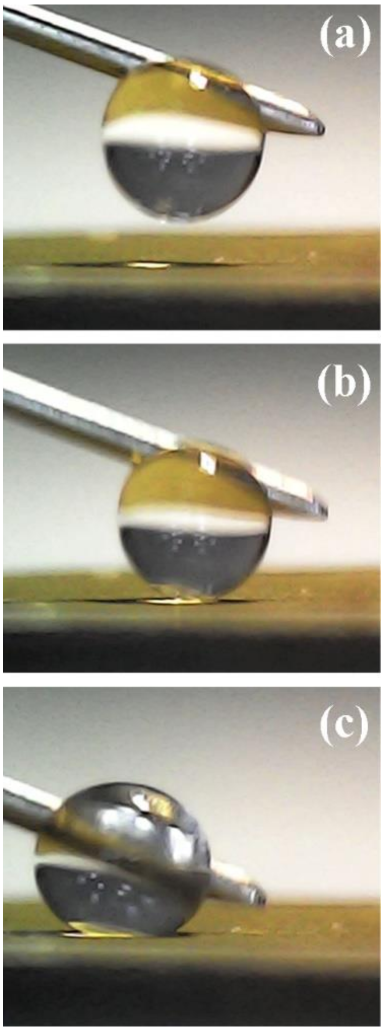

Fig .6. Indicating the SHB behavior of the irradiated brass surface (B1) after 60 days.

Figure 7 shows the plot of mass of collected water versus time for pristine and patterned brass sheets. It is clear that the amount of collected water from fog using the patterned surfaces is higher than the pristine one. Indicating the important role of surface patterning for water harvesting. The calculated water harvesting rate is 10, 14, and 15.3 mg/cm^2.min for pristine, parallel and triangle patterned samples.

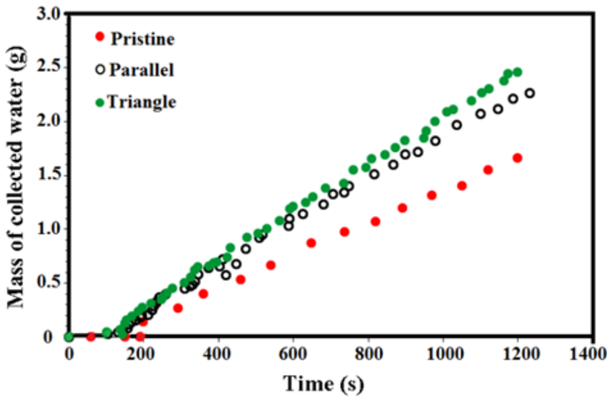

Fig. 7. Mass of collected water versus time for pristine and surface patterned brass sheets.

Fog is made of tiny water droplets suspended in the air. When a solid substrate is exposed to foggy weather, the water droplets are driven to cross or strike the substrate, and many water droplets trapped and placed on the substrate surface. With successive collisions, more droplets coalesce and the number of droplets gradually grows until they are large enough to collapse under the force of gravity [7], [10]. To achieve excellent water harvesting performance, HI/SHB hybrid surfaces were proposed in such a way that the HI regions lead to effective droplet absorption and the SHB parts lead to good water shedding capability [10]. Therefore, as expected, both patterned brass surfaces with hybrid HI and SHB properties indicated more water harvesting efficiency than the pristine brass surface. On the other hand, the shape of HI/HB designed patterns is an important factor for the regulate coalescence and easy removal of water droplets. Because of the surface energy gradient, the immobile droplets on SHB areas preferentially combined with the condensed water on the SHI part leading to facilitate the water droplet growth [7], [22]. The shape of the triangle can create a difference of Laplace pressure from the tip to the base of the triangle, which drives water transport along the surface. When the droplets slide over the triangle

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pattern, all droplets slide in the same line along the surface to the edge of the substrate, exposing more surface area for continuous condensation [7], [22]. As a result, the collection of water increases by triangle pattern.

IV. CONCLUSION

Laser ablation was performed on brass surfaces using a fiber laser at powers of 9, 15, and 21 W in an air environment. This process altered the surface morphology and induced the formation of oxide structures, as confirmed by XRD analysis and SEM images. Immediately following laser ablation, the wetting behavior of the brass, with an initial water contact angle (WCA) of 58º, shifted to a completely SHI state. To assess the aging effect on wettability, irradiated brass samples were exposed to room atmosphere for 60 days, during which the SHI surfaces transitioned to SHB. No change in wettability was observed for pristine samples without laser treatment. These morphological alterations and new structure formations due to laser ablation modified the surface chemistry by absorbing carbon compounds from the air, directly impacting wettability. Utilizing this property, we fabricated hybrid HI/SHB surfaces with parallel and triangular patterns, which were then tested for water harvesting. The investigation revealed that triangular patterns outperformed parallel patterns in water harvesting efficiency.

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