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Surface texturing by indirect laser shock surface patterning for manipulated friction coefficient

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ABSTRACT

Various surface engineering techniques have been developed to improve the tribological performance at tribo-contacts. In particular, research efforts have been put on either enhancing the wear resistance through surface strengthening processes or manipulating the coefficient of friction (COF) through surface patterning processes. A new material process integrating both strengthening and patterning effects might lead to broader impacts in tribology research and applications. In this study, a novel laser-based surface processing technique, named indirect-laser shock surface patterning (indirect-LSSP), is developed. This process utilizes the laser-induced shockwave loadings to introduce the surface strengthening and patterning effects simultaneously, leading to the fabrication of anti-skew surfaces with arrays of micro-indentations for the enhanced wear resistance and manipulated friction values. Indirect-LSSP experiments were carried out on AISI 1045 steels. The 3D surface profiles after LSSP were characterized. The hardness of surface patterns prepared by laser processing was measured. The friction values as affected by laser processing parameters were measured by sliding tests. The relationships among laser processing parameters, micro-feature characteristics, and COF were discussed.

1. Introduction

Tribology is the science that deals with friction, wear and lubrication (Menezes et al., 2013). Tremendous efforts have been made in tribology research with emphasis on enhancing the wear resistance and manipulating the friction value. The wear resistance determines engineering component durability and product quality; while the coefficient of friction (COF), if controlled properly, leads to the required stresses at tribo-pair interfaces for specific performance of engineering structures.

Laser shock peening (LSP) is an effective surface strengthening process used to engineer tribo-contact surfaces for the enhanced wear resistance (Peyre and Fabbro, 1995). In the LSP process, the laser-matter interaction leads to an ultrahigh strain rate plastic deformation (10^5–10^6/s) on the target surface. Consequently, a work-hardened surface layer and compressive residual stresses are introduced (Montross et al., 2002). These beneficial surface alternations make major contributions to the reduced wear rates in tribological performance. Compared with other surface strengthening processes such as shot peening and ultrasonic impact peening, LSP is exceptional in its superior process efficiency, good flexibility, and high controllability. For instance, Wang et al. (Wang et al., 2017) investigated the effect of LSP on abrasion resistance of aluminum alloy 7075. Experimental results demonstrated that the abrasion loss was reduced by 44% after LSP with a laser intensity of 7 GW/cm^2. Lim. et al. (Lim et al., 2012) studied the enhanced wear resistance of a duplex stainless steel by LSP. It was found that the wear volume was reduced by 39% after LSP with a laser intensity of 10 GW/cm^2. Lu et al. (Lu et al., 2012) showed that multiple laser shock peening can significantly improve the wear resistance of AISI 8620 steel. Li et al. (Li et al., 2014) developed a laser peening texturing (LPT) method to fabricate micro-dimple arrays on copper substrate by direct laser shock peening. It was found that this method could reduce both abrasive and adhesive wear. Even if LSP has been successfully applied for enhancing wear resistance, the process efficiency and effectiveness for tribological applications are restricted by the major challenge that, surface strengthening due to plastic deformation is often accompanied by a roughening effect, which leads to deleterious surface micro-features. During sliding at the interfaces of tribo-contacts, these surface micro-features provide stress concentration points, resulting in undesired and uncontrollable friction values.

On the other hand, surface texturing processes such as grinding, etching, embossing, and laser surface texturing (LST), have been developed to create patterned textures on surfaces to control the COF and improve the lubrication lifetime. Among these surface texturing processes, LST holds advantages including scalable, non-contact, no hard tooling, good flexibility, and high resolution (Etsion, 2004). In LST

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process, ultrashort laser pulses are delivered to interact with surface materials for an ablation effect, leading to the generation of surface micro-features. Arrays of surface micro-features produced by LST, such as micro-dimples, can serve as micro-reservoirs for lubricant in the case of lubrication conditions, and micro-traps for wear debris in both lubricated and dry sliding, resulting in the manipulated friction values. As an example, Raeymaekers et al. (Raeymaekers et al., 2007) studied the effect of LST on reducing the COF at magnetic tape/guide interfaces. From their experimental analysis, the reduced friction value was attributed to the formation of an air bearing due to the patterned surface features. Hu et al. (Hu et al., 2012) applied LST to pattern the surface of Ti-6Al-4V alloy. The experimental results demonstrated that the textured surfaces fabricated by LST with a higher micro-dimple density exhibited a lower value of COF. Although the laser-textured surfaces show favorable results for mechanical applications due to manipulated friction values, these surface textures are prone to degradation during extended period of sliding (Qiu and Khonsari, 2011) similar to other mechanically textured surfaces (Menezes et al., 2013). This degradation phenomena is attributed to a low wear resistance of surface textures due to the heating-induced softening effect and the generation of tensile residual stresses during the laser ablation. Therefore, a new surface patterning process design aiming at improving the durability of surface textures is of specific importance. Recent works indicate that lase shock-induced plastic deformation has a great potential to be used for surface patterning (Liao et al., 2012; Ye and Cheng, 2012).

In this study, a novel laser-based surface processing process, named indirect-laser shock surface patterning (indirect-LSSP), is developed. This process utilizes the laser-induced shockwave loadings to introduce the surface strengthening effect and patterning effect simultaneously, leading to the fabrication of anti-skew surfaces with arrays of micro-indentations for the enhanced wear resistance and manipulated friction values. The indirect-LSSP experiments were carried out on AISI 1045 steels to fabricate surface textures of micro-indentations with various depths. The 3D surface profiles after LSSP were characterized by an optical profilometer and scanning electron microscope (SEM). The surface hardness values in the patterned areas were measured by a Vickers Hardness test machine. The friction values as affected by laser processing parameters were measured using a scratch tester. The relationships among laser processing parameters, micro-feature characteristics, and COF were discussed. Note that, the development of direct-LSSP process for fabrication of skew surfaces with arrays of micro-protrusions will be presented in another effort.

2. Experimental procedure

2.1. Materials

LSSP experiments were carried out on AISI 1045 carbon steel square plates with 1 in. width and 0.5 in. thickness. Before laser processing, the specimens were ground against wet emery papers of 220, 400, 600, 800 and 1000 grit size. Diamond polish suspensions of 3 μm and 1 μm were used for the fine polish, and 60 nm colloidal silica suspension was used for the final polish. This polishing process aims to achieve a random surface texture with an average surface roughness of less than 20 nm.

2.2. Indirect-LSSP

The configuration of indirect-LSSP process is illustrated in Fig. 1. In the indirect-LSSP process, a micro-mold with micro-features is placed on the target surface. The ablative coating material is evenly sprayed or coated on top of the micro-mold to absorb the laser energy and protect micro-molds and target surfaces from undesired laser damages. On top of the ablative coating, a transparent confinement is placed to constrain the hydrodynamic expansion of laser-induced plasma for the generation of laser-induced shockwave with a high peak pressure. Once the peak pressure of laser-induced shockwave is higher than the dynamic yield strength of the target material, the high strain rate surface plastic deformation is induced, leading to the fabrication of anti-skew surfaces with arrays of micro-indentations. In this process, the micro-mold serves as a mask and a cushion for patterning, and does not directly interact with laser energy.

In this study, TEM grids with a mesh size of 400 and a diameter of 3.05 mm were used as micro-molds. Graphite and BK7 glass were employed as the ablative coating and the confinement media, respectively. A Q-switched Nd-YAG laser with a wavelength of 1064 nm and a pulse duration of 7 ns was used to deliver the laser energy. In order to understand the effect of laser processing parameters, LSSP experiments were carried out with various laser intensities. After processing, the BK 7 glass and TEM grid were removed, and the remained graphite was throughly cleaned.

2.3. Morphology characterization and mechanical property testing

The 3D morphology of patterned surfaces was characterized by SEM (JEOL-2100) and an Rtec 3D optical profilometer. The depth and width of patterned features as affected by laser processing conditions were systematically studied. Tribological tests were conducted on the patterned steel plates by using Rtec Multi-function tribometer 5000. In the tribo-pair sliding test, aluminum alloy 6061-T6 (AA6061) was selected to make the pins with dimensions of 10 mm in length, 3 mm in diameter, and 1.5 mm in tip radius. The pins were slid under a normal load of 50 N over a distance of 10 mm at a sliding speed of 2 mm/s. The tests were conducted in a dry condition under the ambient environment. The COF as affected by the patterning effect was recorded. After the sliding test, the transfer layers formed on the steel plates were analyzed by SEM and Energy Dispersive X-Ray Spectroscopy (EDS). The surface hardness values before and after processing were measured by a Leco M-400-H micro hardness test machine. Hardness tests were carried out using a 500 g load and a 10 s holding time.

3. Results and discussion

3.1. Surface micro-patterns prepared by LSSP

Fig. 2 shows the surface morphology of the specimen generated by LSSP with a laser intensity of 0.554 GW/cm^2. As observed in Fig. 2, the shape of the mold (TEM copper grid) is well taken by the substrate, showing array of squared indentations with a width of 37 μm. The observed micro-indentations indicate that a severe plastic deformation is induced by laser shock loadings in the hole areas of TEM grid. On the other hand, in the bar areas of TEM grid, no significant deformation is observed as the mechanical energy of laser shockwave is absorbed by the copper grid, which serves as a cushion layer. Fig. 2b and c show a 3-D image and a 1-D profile of micro-indentations, respectively. It is observed that the indentation depth generated by LSSP is around 0.43 ± 0.07 μm. As compared to the work reported by Li et al. (Li et al., 2014), in which microscale indentation features were fabricated one by one, indirect-LSSP offers a scalable approach where a number of micro-indentations were generated simultaneously by one laser pulse. Note that the ratio of height to width of the patterned features fabricated by LSSP in this work (Fig. 2) is lower than that of features prepared by other laser surface texturing methods. This is attributed to the large mesh size, low laser intensity, and high strength level of target material (AISI 1045 carbon steel) used in this research. It is expected to achieve a higher height-width ratio of micro-features by indirect-LSSP if a smaller mesh size mold, a higher laser intensity, and a softer target material are utilized for experiments (such as aluminum alloy).

In the indirect-LSSP process, the depth of micro-indentations is strongly affected by the peak pressure of laser shock loadings which is dependent on the laser power intensity. The shockwave pressure, P, as a function of the laser intensity, I, can be estimated by the well-accepted laser shock processing model proposed by Fabbro et al.(Fabbro et al.,

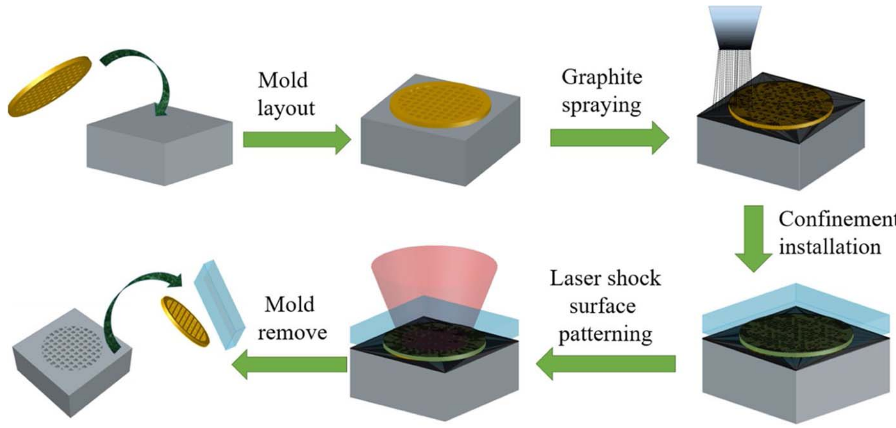

Fig. 1. A schematic illustration of indirect-LSSP process.

1990):

$$\frac{dL(t)}{dt} = P(t)(\frac{1}{Z_1} + \frac{1}{Z_2}) \quad (1)$$

$$I(t) = P(t)\frac{dL}{dt} + \frac{3}{2\alpha}\frac{d}{dt}[P(t)L(t)] \quad (2)$$

where t is the laser loading time, L is the thickness of the plasma interface, and Z_1 and Z_1 are the shock impedances of the target material and confinement, respectively. In this work, the shock impedances for 1045 steel and BK 7 glass are $3.96 \times 10^6$and $1.44 \times 10^6 g/cm^2s$, respectively (Ding and Ye, 2006).

According to Fabbro's model, the temporal evolution of laser shockwave pressure as affected by the laser intensity is shown in Fig. 3a. It is observed that the shockwave peak pressure increases with the increase of laser intensity. For instance, by increasing the laser intensity from 0.484 to 0.890 GW/cm^2, the peak pressure of laser shockwave is enhanced from 1.6 to 2.3 GPa, which is much higher than the dynamic yielding strength of the AISI 1045 steel used in this experiment (around 310 MPa). Fig. 3b shows the indentation depth as affected by the laser intensity in indirect-LSSP. It is clearly observed that the indentation depth increases by increasing the laser intensity. As an example, the indentation depth increases from 0.21 to 0.75 μm by increasing the laser intensity from 0.484 to 0.890 GW/cm^2.

3.2. Tribological properties as affected by LSSP

Cross-over scratch tests were carried out to study the patterning effect introduced by LSSP on the friction value. Fig. 4 shows the results of scratching tests on a laser-patterned surface prepared by LSSP with a laser intensity of 0.554 GW/cm^2. It is observed that the COF is dramatically reduced from 0.36 to 0.28 from the base surface to the laser-patterned surface. The similar phenomenon of the patterning effect on the reduction of COF was also reported by other researchers. Li et al. (Li et al., 2016) showed that the hot-embossed patterned micro-features on a bulk metallic glass could reduce its COF from 1.05 to 0.45. Bathe et al. (Bathe et al., 2014) reported that a dramatic drop of COF on the surface of a gray cast iron was achieved by laser surface texturing. They both attributed the reduction of COF to the decrease of contact area during the sliding due to the existence of skew micro-patterns. Further, Menezes et al. (Menezes et al., 2008) reported that the COF can be manipulated over 200% by patterning the surfaces.

LSSP experiments were conducted with various laser intensities to study the effect of laser intensity on COF, as shown in Fig. 5. It can be seen that the friction value of laser patterned surface can be manipulated by adjusting the laser intensity. As an example, given a low laser

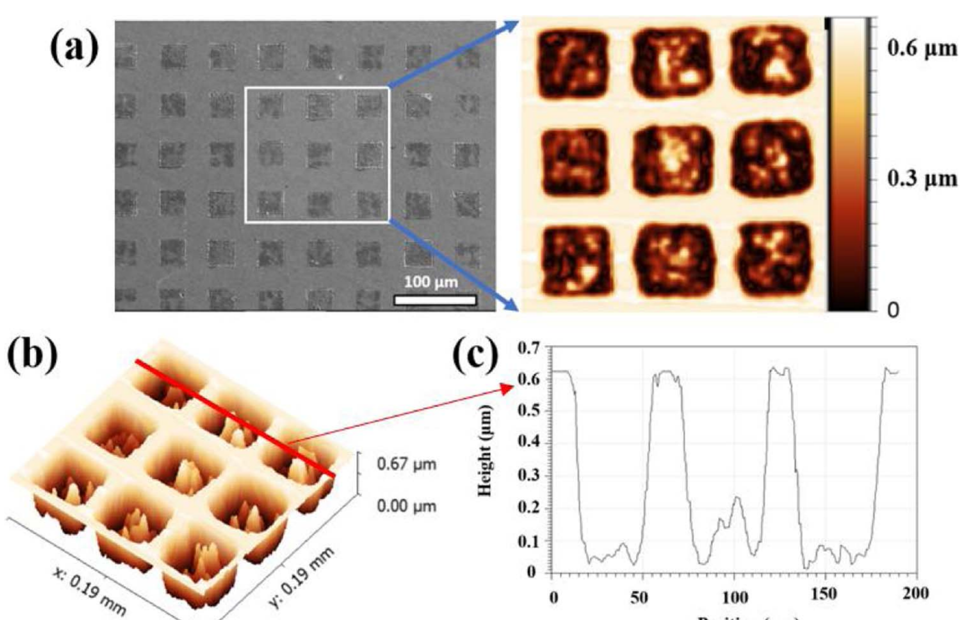

Fig. 2. (a) a SEM image and a 2-D optical image of the patterned surface, (b) a 3-D image of patterned micro-indentations, and (c) a 1-D profile of micro-indentations.

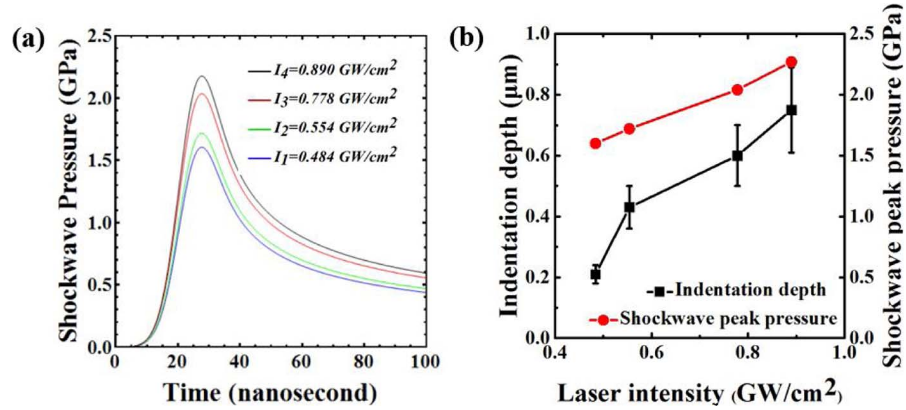

Fig. 3. (a) The temporal evolution of laser shockwave pressure as affected by the laser intensity, estimated by Fabbro's model, and (b) the indentation depth generated by indirect-LSSP at various laser intensities.

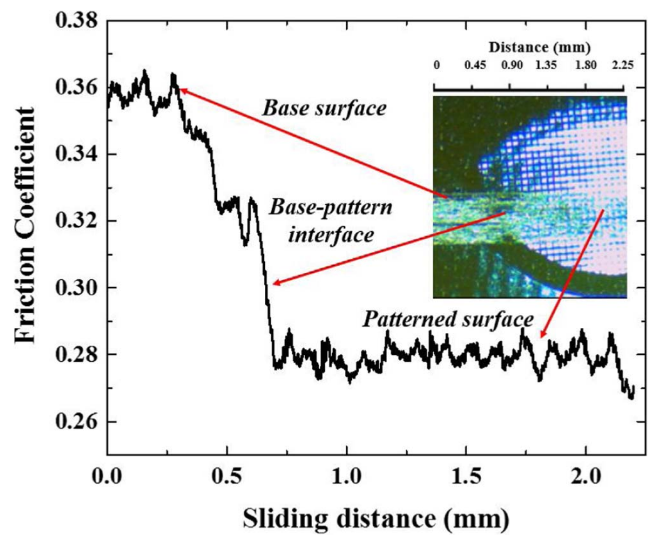

Fig. 4. Cross-over scratch tests under a dry condition: the COF on base and patterned surfaces prepared by LSSP with a laser intensity of 0.554 GW/cm^2.

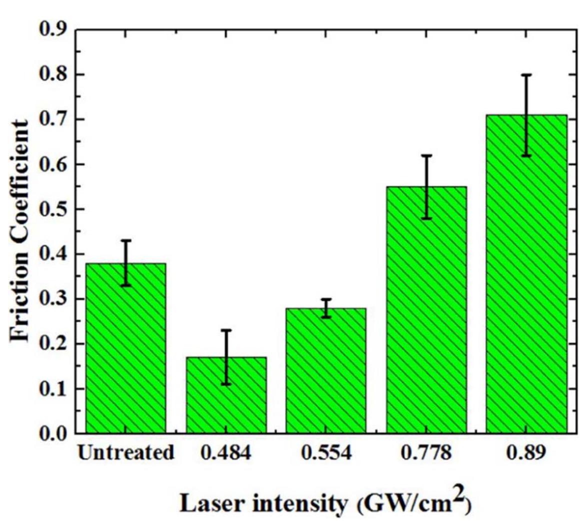

Fig. 5. Effect of laser intensity on COF.

intensity of 0.484 and 0.554 GW/cm^2, the COF was reduced by 55% and 26% from 0.38 to 0.17 and 0.28, respectively. On the other hand, given a high laser intensity of 0.778 and 0.890 GW/cm^2, the COF was increased by 45% and 87% from 0.38 to 0.55 and 0.71, respectively.

In order to obtain a better understanding of the laser intensity effect on the friction value, surface profiles of the patterned surfaces fabricated by LSSP with various laser intensities were characterized by an optical profilometer, as shown in Fig. 6. It is observed in Fig. 6 that, in addition to the indentation depth (Fig. 3b), the roughness and width of indentations are also affected by the laser intensity. With a higher laser intensity, surface topography tends to have a narrower band with a sharper edge geometry, and the surfaces of indentation bottom areas exhibit a greater roughness. Fig. 7 schematically illustrates the laser intensity effect on the contact conditions between the pin and patterned substrate prepared by LSSP. Given a high laser intensity such as 0.890 GW/cm^2, due to the deeper indentation depth and the narrower bands, the penetration depth of the sliding pin at the tribo-pair interface is deeper, as compared to it is under the condition sliding against the patterned surface prepared by LSSP with a low laser intensity such as 0.448 GW/cm^2. This deeper penetration is attributed to more stress concentration induced by the sharper edge geometry, which leads to that a greater shear stress is needed to sustain sliding. Moreover, as the surface roughening effect increases with the increased laser intensity, there might be more asperities interlocking at the indentation bottom areas. These changes of surface morphology lead to the increase of COF with the increased laser intensity. According to experimental results and analysis, it can be seen that for a patterned surface, the determination of the COF is much more complex than an untreated flat surface. It involves mechanisms including the resistance force from the indentation edge, the interlocking of asperities at the tribo-pair interfaces, and the change of surface strength (Menezes et al., 2013). A quantitative relationship between the COF and the surface patterning parameters needs to be further investigated.

Further analysis of tribology properties as affected by LSSP was conducted by using SEM and EDS phase mapping analysis. Fig. 8a is a SEM image showing the patterned surface after the scratching test. The formation of transfer layer on the sample surface is clearly observed in Fig. 8a. Fig. 8b is an EDS image showing the phase mapping of Al element on the sample surface after the scratching test. As observed in Fig. 8b, a larger amount of transferred Al element is formed on the patterned area than that on the untreated area. This phenomenon might be attributed to the trapping effect of indentations, which are usually considered as traps for wear debris in dry contacts. In this study, although the surface strengthening effect introduced by laser shock processing has a positive effect on the wear resistance, the square-shaped indentations prepared by LSSP provide a deleterious effect due to the high stress concentration at tribo-pair interfaces, which is attributed to the sharp square corners (Menezes et al., 2013). A better design of patterned indentations such as round-shaped might lead to a significant improvement of wear resistance. This will be addressed in our future research.

To have a better understanding of surface hardening effect on the wear performance of laser processed samples, the surface hardness

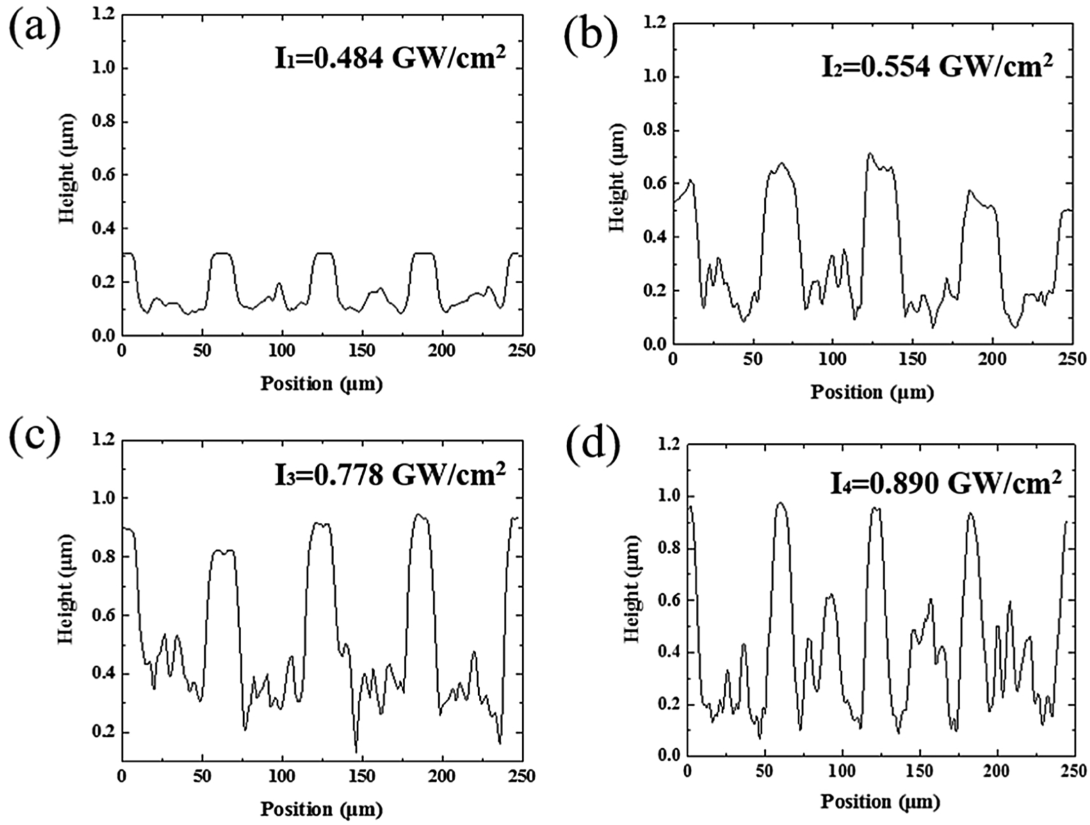

Fig. 6. Surface profiles of the patterned surfaces fabricated by LSSP with various laser intensities: (a) 0.484 GW/cm^2, (b) 0.554 GW/cm^2, (c) 0.778 GW/cm^2, and (d) 0.890 GW/cm^2.

values of AISI 1045 steels processed by indirect-LSSP with different laser intensities were measured by a Vickers hardness test machine. In order to measure the hardness value of microfeature bottom areas, LSSP experiments were conducted using a TEM copper grid with a mesh size of 420 μm. Fig. 9a shows an optical microscopy image of the copper grid template. Fig. 9b shows the surface patterns generated by LSSP with a laser intensity of 0.554 GW/cm^2. It can be seen that the width of the patterned features is around 420 μm. Fig. 9c shows the effect of laser intensity on the micro-hardness of the patterned features. It can be seen that the hardness value increases by increasing the laser power intensity. For instance, the hardness increases from 212 VHN (Vickers Hardness Number) for the untreated specimen to 238 VHN for the specimen processed by LSSP with a laser intensity of 0.890 GW/cm^2. The hardness improvement is attributed to the work hardening effect induced by laser shock loading, and is expected to lead to enhanced wear resistance of the LSSP treated specimen. However, in addition to the surface strength, the wear resistance is also strongly affected by the dimensions, shape, and density of laser-patterned micro-features as well as the sliding load and velocity in the scratch test. Given the complexity of the mechanism of wear resistance, it will be studied in our next research, in which scratch tests will be conducted between a diamond pin and the laser-patterned surface. LSSP experiments will be systematically designed to understand the wear performance as affected by microfeature dimensions, shape, and density. Scratch tests will be carried out with various sliding loads and velocities. The wear weight loss and scratch depth will be measured, and the contribution of surface patterning and hardening effects on the wear resistance will be studied in details.

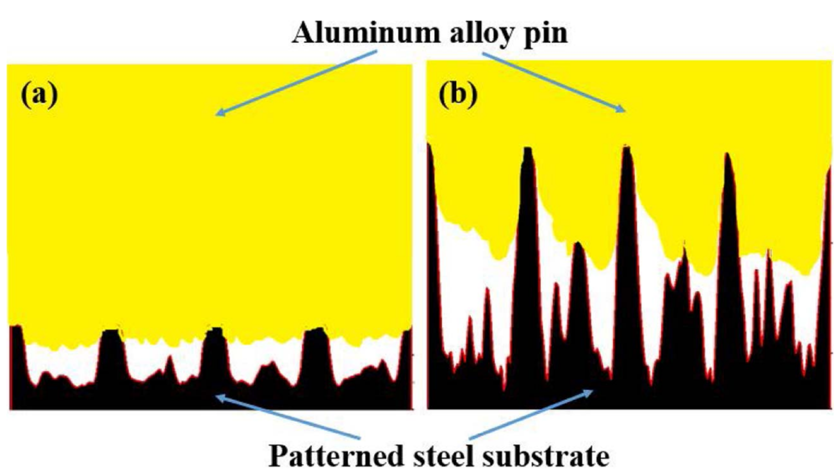

Fig. 7. Schematic illustration of contact conditions between the aluminum alloy pin and the patterned steel substrate processed by LSSP with a laser intensity of (a) 0.448 GW/cm^2 and (b) 0.890 GW/cm^2.

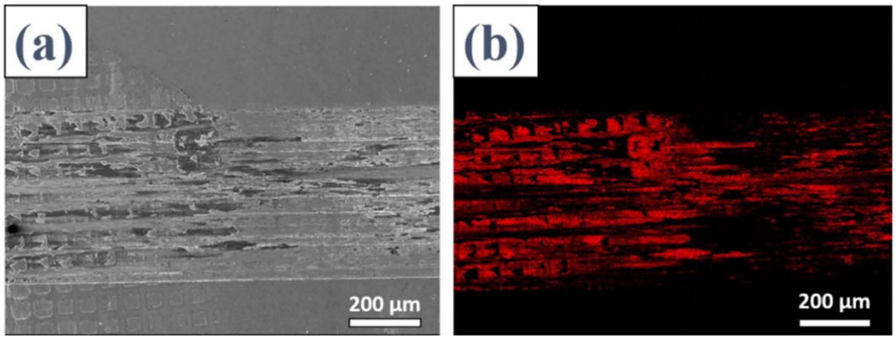

Fig. 8. Laser patterned surface after the scratching test: (a) a SEM image, and (b) EDS phase mapping of Al element. Surface micro-pattern is prepared by LSSP with a laser intensity of 0.554 GW/cm^2.

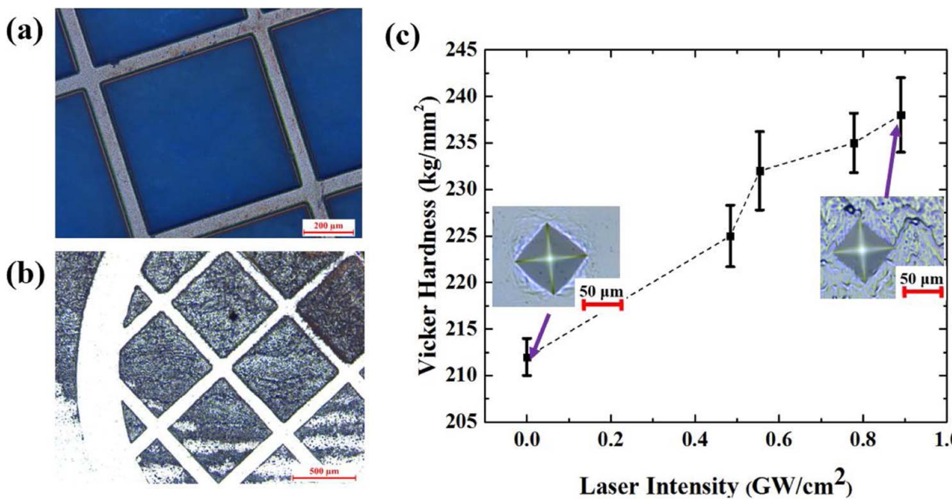

Fig. 9. (a) An optical microscope image of copper grid template with a mesh size of 420 µm, (b) an optical microscope image of surface patterns generated by indirect-LSSP, and (c) effect of laser intensity on the hardness value of microfeature bottom area.

3.3. What is anticipated?

Further development and investigation on LSSP will be conducted in future research. LSSP is expected to have the following features:

1) *Both skew surface with micro-protrusions and anti-skew surface with micro-indentations are realized*. In the indirect-LSSP process presented in this work, an ablative coating layer is placed on top of the micro-mold to absorb the laser energy and protect micro-molds and target surfaces from undesired laser damages. The micro-mold does not directly interact with laser energy, and serves as a mask and a cushion for patterning, resulting in the generation of anti-skew surface with micro-indentations. On the other hand, in the direct-LSSP process, the micro-mold is placed on top of a protective layer of sample substrate. The micro-mold is applied not only to deliver the pattern features, but also to serve as ablative materials for a direct interaction with the laser energy, leading to the generation of skew surface with micro-protrusions.
2) *Manipulated COF is realized*. By adjusting the laser processing conditions, the size, depth, geometry, and roughness of patterned micro-features can be controlled. Therefore, the tailored surface morphology will lead to a manipulated friction value.
3) *Enhanced wear resistance of surface micro-features is realized*. LSSP introduces surface strengthening and patterning effects simultaneously. The enhanced surface strength will lead to an improved wear behavior of micro-features in sliding contact. In addition, a designed geometry of micro-features such as round-shaped aiming at minimizing the contact stress at the tribo-pair interfaces might have a significant impact on the wear performance of surface micro-features.
4) *It is a scalable surface patterning process with a high process flexibility*. LSSP is a fast and scalable manufacturing process, which can be carried out at room temperature and without a vacuum system requirement. The laser beam has an excellent spatial resolution that makes LSSP ideal for localized processing of components with various shapes and sizes.

4. Conclusions

A novel laser-based surface patterning process, named indirect-LSSP, is presented in this paper. This process utilizes the laser-induced shockwave loadings to introduce the surface strengthening and patterning effects simultaneously. As a result, anti-skew surfaces with patterned micro-indentations are successfully fabricated by indirect-LSSP. The scratching tests on laser patterned surfaces indicate that COF can be manipulated by adjusting the laser intensity. With a higher laser intensity, the indentation depth is increased, surface topography tends to have a narrower band with a sharper edge geometry, and the surfaces of indentation bottom areas exhibit a greater roughness. These changes of surface morphology make major contributions to the manipulated friction value. In addition, SEM and EDS phase mapping analysis indicate that, although the surface strengthening effect has a positive effect on the wear resistance, the square-shaped indentations with sharp corners prepared by LSSP in this work provide a deleterious effect. We envision that further investigation and development of LSSP process will lead to the fabrication of patterned surfaces with desired tribology properties, in particular the manipulated COF and the enhanced wear resistance. Therefore, LSSP has a great potential in widespread industrial applications, such as micro-gears of a MEMS transmission, and surface patterning of magnetic storage devices.

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