

Laser surface texturing and related techniques for enhancing tribological performance of engineering materials: A review

Bo Mao, Arpith Siddaiah, Yiliang Liao*, Pradeep L. Menezes*

Department of Mechanical Engineering, University of Nevada, Reno, NV 89557 USA

ARTICLE INFO

Keywords:

Laser surface texturing
Laser ablation
Laser shock processing
Texture design
Coefficient of friction
Wear resistance

ABSTRACT

Surface texturing is one of the most efficient surface modification approaches for improving the tribological performance of engineering materials. Several surface texturing techniques have been developed in recent years. Among these methods, laser surface texturing (LST) has gained considerable interests due to its high flexibility, superior texturing accuracy, and good controllability. This paper reviews the recent advances and developments of LST for enhanced tribological properties of engineering materials. The process designs of LST by means of direct laser ablation, laser interference, and laser shock processing are discussed. The effects of laser parameters on the texture features are highlighted. The enhanced tribological properties of LST-processed materials and their applications on various fields are reviewed. The current challenges and future directions of LST techniques are discussed.

1. Introduction

Friction and wear are two major concerns in various engineering applications where surface interactions exist. Tremendous research efforts have been made to control the tribological performance of materials where mating surfaces are slide against each other with manipulated surface textures [1–3]. Surface texturing has been perceived as an efficient and widely used approach to modify the interaction between surfaces for better lubrication, controlled friction, and enhanced wear resistance of engineering materials [4–7]. The first successful practice of surface texturing can be dated back to 1940s, when an “interrupted surface finish” in the diesel engine piston ring-liner interface was developed to prevent seizure under hot running conditions [8]. In 1960s, Anno et al. [9] proposed their theory on micro asperity lubrications by introducing protrusions to improve the tribological performance. In the late 90’s, Etsion et al. [10–12] reported that micro-dimples on the surface of mechanical seals can be used to reduce the friction and improve the wear resistance. Recently, the state of the art of surface texturing applied to mechanical components was summarized by Rosenkranz et al. [13] and Grützmacher et al. [14]. To date, the effect of surface texturing on the tribological performance of engineering materials has been extensively studied experimentally and theoretically.

Various surface texturing techniques have been developed over the years, including laser surface texturing (LST) [15], ion beam etching/milling [16], lithography [17], hot embossing [18], micro-milling [19],

electrochemical machining [20], and mechanical texturing [21]. Among these methods, LST has gained considerable attention due to its unique advantages including: fast, high efficiency, good controllability, environmental friendly nature, and the capability of fabricating surface texture with high complexity and accuracy [22–25]. Due to these advantages, LST has been widely used in various applications to improve the tribological performance of engineering components with contacting surfaces, such as mechanical seals [26], thrust bearing [27], piston rings [28], and magnetic storage devices [29]. Moreover, it has also been utilized to improve the tribological performance of a variety of materials from metals [30,31] to ceramics [32,33] and polymers [34,35].

Several reviews in literature focused on the progress of LST techniques [24,36–38], where the effect of LST on tribological performance has been detailed by Etsion [39] and Bonse et al. [40]. However, these papers only focus on the LST by means of laser ablation. In recent years, novel laser-based material processing processes, such as laser interference and laser shock processing, emerge as alternative methodologies expanding impacts of LST techniques on tribological applications. Therefore, it is of great importance to have a comprehensive review of the current advances of LST on improving tribological performance of engineering materials.

The objective of this paper is to present a comprehensive review on the state-of-the-art of the LST techniques for enhancing the tribological properties of engineering materials. The process designs of LST

* Corresponding authors.

E-mail addresses: yliiao@unr.edu (Y. Liao), pmenezes@unr.edu (P.L. Menezes).

techniques by means of direct laser ablation, laser interference, and laser shock processing are reviewed and compared. The effects of laser processing parameters on the morphology of the textured surface are studied. The LST-enhanced tribological performance in terms of manipulated coefficient of friction (COF) and improved wear resistance of engineering materials is discussed. Furthermore, the utilization of LST for various applications are presented followed by the discussion and outlook of the current challenges and future directions of the LST techniques.

2. Process design

Based on the mechanisms responsible for surface texture fabrication, the current LST techniques can be divided into three groups, including: (1) direct material removal by means of laser-induced ablation, (2) material melting by laser interference, and (3) material shaping and patterning by laser shock induced surface plastic deformation. This section reviews the state-of-the-art of these three approaches in terms of mechanism, design, advantages and disadvantages.

2.1. LST by direct laser ablation

Laser ablation is a process of removing materials from a solid surface by irradiating it with a laser beam. Upon the absorption of laser energy, the laser-matter interaction leads to the evaporation of surface materials, which can be further ionized to form a plasma at a high laser flux [41–43]. During the laser ablation process, localized materials loss is achieved, resulting in a surface texture with specific design patterns, such as micro-dimples or grooves.

LST by means of direct laser ablation has been successfully applied to many engineering materials. For instance, Baurngart et al. [29] fabricated micro-bump patterns with a diameter of around 20 μm on the ultra-smooth silicon disk by direct laser ablation process. Wang et al. [44] showed that a cone-array-like microstructure with a spike depth up to 8 μm can be fabricated on a silicon wafer by direct laser ablation. Hu et al. [45] carried out a study on under-water laser ablation of stainless steels, in which micro-dimples with a diameter between 200–1000 μm were successfully fabricated on sample surfaces. Fang et al. [46] performed LST on an $\text{Al}_2\text{O}_3/\text{Mo}$ laminated composite by using a commercial pulsed Q-switched Nd: YAG laser with a wavelength of 355 nm. Both micro-dimples and micro-grooves were fabricated on the surfaces of the samples. Li et al. [47] created surface crater arrays on alumina ceramics. A schematic illustration of the set-up for LST by laser ablation is illustrated in Fig. 1a, in which a textured groove is fabricated on the surface of ZrO_2 ceramics [48]. A Nd-YAG laser with a wavelength of 1064 nm and a pulse duration of 10 ns was used for laser processing. Fig. 1b shows the 3-D surface profile of the sample after LST. It can be seen that a textured groove with a width of 30 μm and a depth of 12 μm is generated on the surface of the sample. LST by means of laser ablation holds the advantages of high efficiency and controllability. However, its accuracy and flexibility are sometimes limited by the laser type, laser beam size and pulse energy [41,42].

2.2. LST by laser interference

Laser interference, also known as direct laser interference patterning (DLIP), serves as another effective LST approach in which a periodic pattern of features is created by means of the interference of coherent laser beams [49,50]. During the laser beam interfering process, the surface material of the samples is locally melted at the position of maximum interference which corresponds to the highest laser intensity. The materials transfer from the interference maxima to the minima positions due to the surface tension gradient caused by temperature gradient [51]. Periodic surface geometries, such as line, dot, and cross-like patterns, can be fabricated on the surfaces of various materials by DLIP [52]. The gap between the texture features fabricated

by laser interference is determined by the laser wavelength, laser-target distance, and the distance between the two laser beams [50,53].

LST by means of laser interference has also been applied to various engineering components. For instance, Aguilar-Morales et al. [54] utilized laser interference to fabricate a high aspect-ratio line-like and pillar-like periodic structure on stainless steels. Bieda et al. [51] used the direct laser interference method to fabricate one and two dimensional periodic micropatterns on 100Cr-steel surfaces. A schematic view of the setup in their experiment is shown in Fig. 2a. The primary coherent laser beam was split into several beams by one or two beam splitters. The beams were recombined to interfere on the sample's surface with highly reflective mirrors. A mechanical shutter and a telescope system were used to control the number of pulses and beam size, respectively. The laser-processed surface morphologies with periodic grooves were shown in scanning electron microscope (SEM) images in Fig. 2b-d. It can be observed that line-like surface patterns were developed on the sample surface due to the periodic variation of the laser intensity. Moreover, increasing the laser intensity from 0.8 to 1.6 J/cm^2 resulted in more pronounced and deeper patterns due to a higher amount of melted materials. Compared with laser ablation, laser interference brings a higher texture resolution and a smaller heat affected zone [49,55]. Moreover, it allows the producing of some complex texture features by adjusting the angles of the sub-beams, laser wavelength, and pulse energy [56]. Fig. 3 shows a comparison of different surface texturing techniques in terms of structure size and fabrication speed [53]. As observed in Fig. 3, laser interference can reach a fabrication speed of 0.1 m^2/min with a structure size ranging from 1 to 100 μm , which demonstrates the superior processing efficiency as compared to lithography and laser ablation. The most prominent advantage of laser interference as compared with LST with direct laser ablation is its capability to fabricate texture feature with a high resolution. Choi et al. [57] showed that uniform dot patterns with the half pitch size of around 190 nm can be fabricated on a silicon substrate by laser interference.

It should be noted that materials processed by laser interference texturing can be locally ablated at the position of maximum interference if sufficient laser energy is utilized [54]. Alamri et al. [58] showed that both laser ablation and melting process could be involved in the process of producing surface patterns, depending on the type of processed materials, laser duration time, and laser pulse energy. However, since laser ablation is always accompanied with surface roughening effect and low texture resolution, most of the laser interference texturing study for improving the tribological performance of metallic materials were carried out via laser induced-remelting [51,59–62]. Therefore, laser interference texturing is excluded from direct laser ablation in the current text of this paper.

Despite the advantages offered by LST via direct laser ablation and laser interference, the heating effect in these approaches may lead to undesired by-products such as material degradation, phase transformation, and thermal-induced tensile residual stresses. Several studies demonstrate that surface patterning of steels through laser ablation is often accompanied with phase transformation [63,64]. For instance, Syed et al. [65] showed that the ferrite phase in a low carbon steel was transformed into a harder phase of martensite or bainite after LST by direct laser ablation. Even though the phase with a high strength level can contribute to the increased wear resistance [66], it might lead to the formation of surface cracks and generation of tensile residual stress, resulting in a poor durability of processed samples [67]. Moreover, surface oxidation is another critical concern [68]. As demonstrated by Martinez et al. [69], a layer of titanium dioxide was produced on the surface of UNS R56400 titanium alloy processed by laser ablation, leading to a nearly 20 % decrease of COF.

2.3. LST by laser shock processing

To tackle the challenges of laser ablation and laser interference,

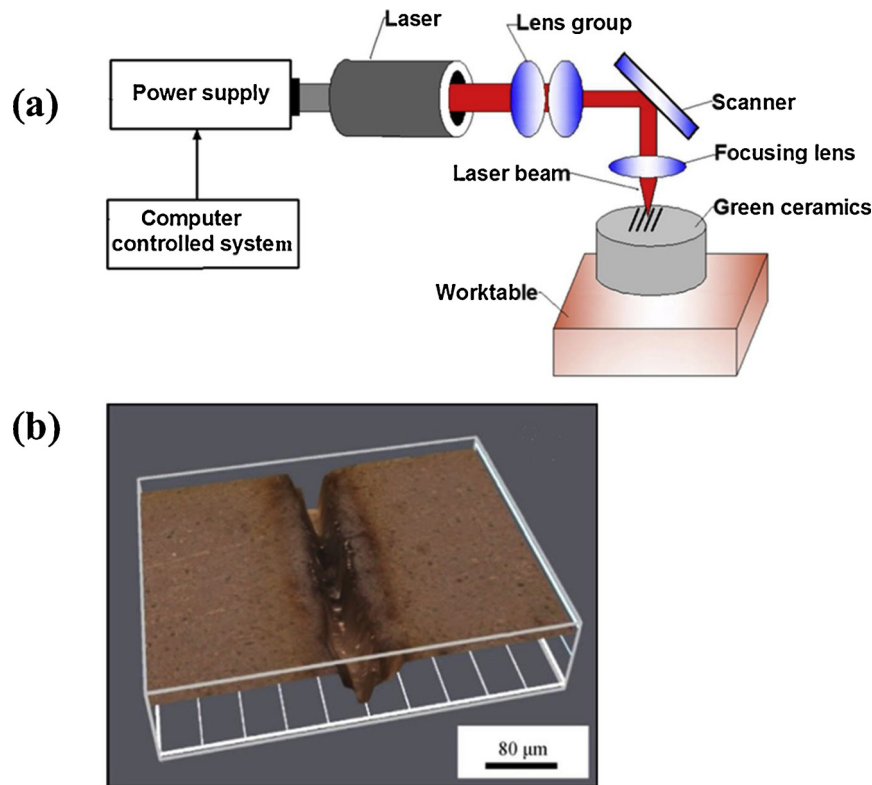


Fig. 1. (a) Schematic diagram of LST process of ZrO₂ ceramics and (b) 3D surface profiles of the textured groove processed by LST with a frequency of 20 Hz, a power of 4 W and a scanning speed of 150 mm/s [48].

novel LST techniques based on laser shock processing (LSP) have been developed in recent years. LSP is an advanced laser-based surface engineering process, in which laser-induced shockwave is utilized to introduce compressive residual stress as well as surface hardening effect on the target surface [70,71]. The surface texture is generated by laser shock induced plastic deformation without a thermal effect [72]. A schematic view of LST by LSP is shown in Fig. 4a [73]. The target material is covered with an opaque coating to absorb the laser energy. A transparent confinement is laid on the coating. During the LSP process, laser pulse interacts with the opaque coating instead of the target material, resulting in the formation of laser-induced plasma. The expansion of the plasma is restricted by a transparent confinement, leading to the generation of laser-induced shockwave (with a high peak pressure on the order of GPa) propagating into the target material. Once the shockwave pressure exceeds the dynamic yield strength of the target materials, ultrahigh strain rate plastic deformation ($10^5/s$ – $10^6/s$) occurs on the surface of processed samples [74]. As a result, surface texture with micro or mini-dimples can be created by LSP, as shown in Fig. 4b.

Several studies have shown that LSP could effectively improve the wear resistance of metallic materials [75–78]. The main mechanism responsible for the improved wear resistance is the combined effect of the surface hardening and residual stress [77]. For example, Li et al. [73] fabricated micro-dimple arrays on copper by LSP. It was found that LSP-processed surfaces exhibited improved tribological performance with both reduced abrasive and adhesive wear as compared to the untextured surface. Yakimets et al. [77] showed that the wear rate of a rolled 100Cr steel can be reduced by 33 % using LSP. Lim et al. [79] demonstrated that micro-hardness values of duplex stainless steels increased from 250 HV to 310 HV after LSP treatment. As a result, the wear rate was reduced by 16 %. Although the LSP can generate a surface hardening effect for enhanced wear resistance, this process exhibited a low efficiency since the micro-features (such like dimples shown in Fig. 4b) need to be fabricated one by one. Such a low process

scalability strongly restricts the applications of LSP-based LST in real industry.

To integrate the surface texturing and surface hardening effect, Mao et al. [80] proposed a novel processing strategy, named indirect-laser shock surface patterning (LSSP), for scalable fabrication of surface patterns by LSP. As shown in Fig. 5a, in the indirect-LSSP process, a micro-mold with micro-features was placed on the target surface. The ablative coating material was 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 damage. On top of the ablative coating, a transparent confinement was placed to constrain the hydrodynamic expansion of laser-induced plasma for the generation of laser-induced shockwave with a high peak pressure. Due to laser-matter interaction, the high strain rate surface plastic deformation was induced, leading to the fabrication of anti-skew surfaces with arrays of micro-indentations. In this process, the micro-mold does not directly interact with laser energy, however, serves as a mask and a cushion for the patterning. The SEM and surface profile of the micro-indentations are shown in Fig. 5b. It can be seen that surface features with a width around 40 μm and a depth around 0.43 μm were generated on the surface of the sample. Compared with other methods, indirect-LSSP offers a scalable approach where a number of micro-indentations were generated simultaneously by one laser pulse.

In summary, a comparison of LST techniques by means of direct laser ablation, laser interference, and LSP is summarized in Table 1.

3. Effects of laser parameters on surface texturing

In the LST processes, besides the selection of laser types, the surface morphology and feature sizes can be controlled by adjusting the laser processing parameters, such as laser power intensity, laser spot size, and pulse repetition frequency. Understanding their effects on surface texturing will be beneficial for the optimal design of LST processes, and therefore the tribological performance of processed materials. This

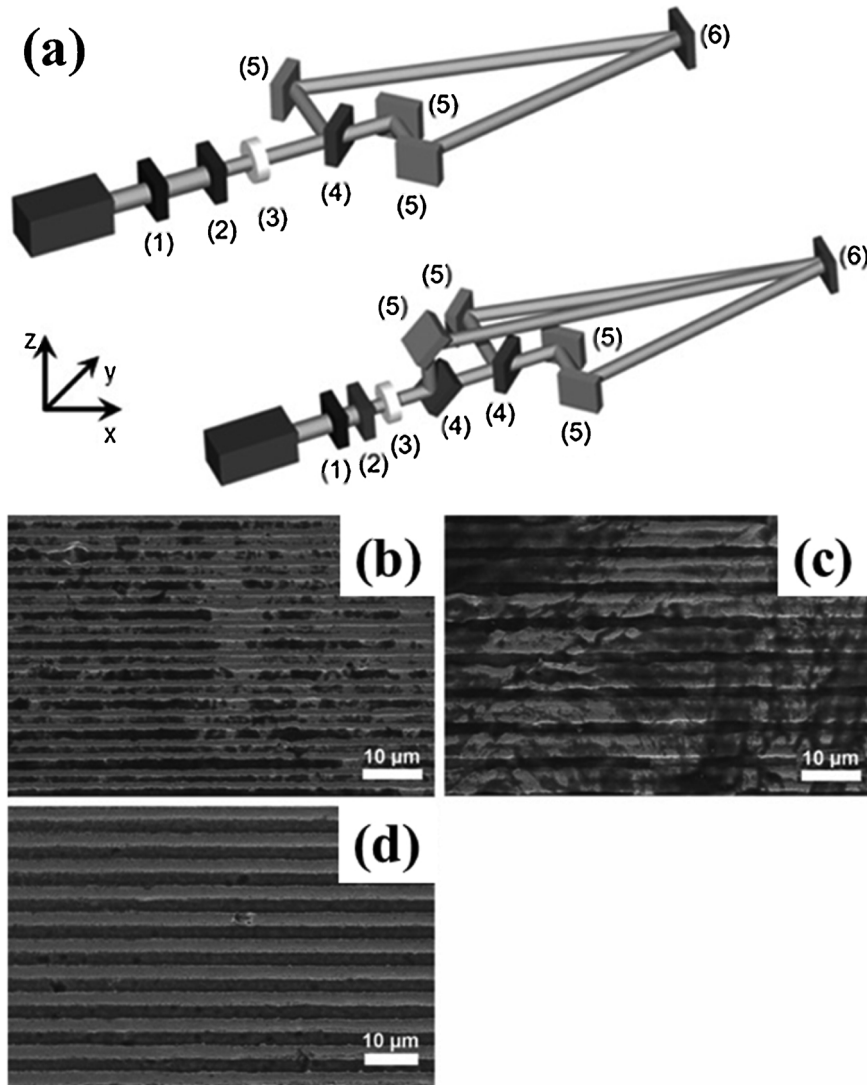


Fig. 2. (a) Schematics of two and three beam laser interference setup: (1–2) Beam expander; (3) mechanical shutter; (4) Beam-splitters; (5) Mirrors; and (6) Substrate. SEM images of line-like patterns fabricated on 100Cr6-steel surfaces with an energy density of (b) 0.8 J/cm^2 , (c) 1.2 J/cm^2 , and (d) 1.6 J/cm^2 [51].

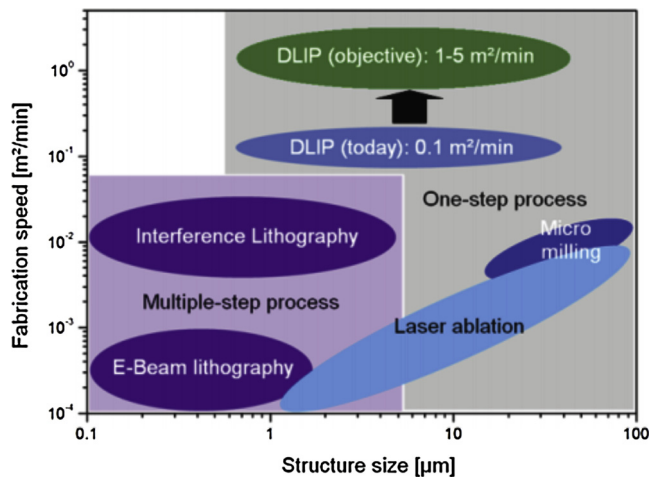


Fig. 3. A comparison of different surface texturing techniques in terms of structure size and fabrication speed [53].

section reviews the important parameters and factors that affect the surface texture and the underlying mechanisms.

3.1. Laser type

The commercial pulse lasers can be distinguished by the laser pulse duration as milli-second, nano-second, pico-second, and femto-second lasers. In the LST processes, the laser pulse duration plays a significant role in determining the process efficiency and effectiveness by affecting the thermal input in laser ablation and interference and the plastic deformation rate in LSP [67,83–85]. For example, Bhaduri et al. [86] compared the surface morphology of the planar tungsten carbide blocks as processed by nano-second and femto-second ablation-based LST. It was found that a few nano-ripples formed in the textures produced with femto-second laser while no such feature was observed in the samples processed by nano-second laser. Bathe et al. [85] used three different lasers to fabricate surface patterns on a gray cast iron. The textured surfaces processed by millisecond, nanosecond, and femtosecond lasers are shown in Fig. 6. It can be seen that the surface processed by millisecond laser was partially melted and the molten materials were ejected from the dimple due to the high energy and long pulse duration. The ejected materials deposited around the dimple and formed a kind of bulge. On the other hand, the sample processed by femtosecond laser

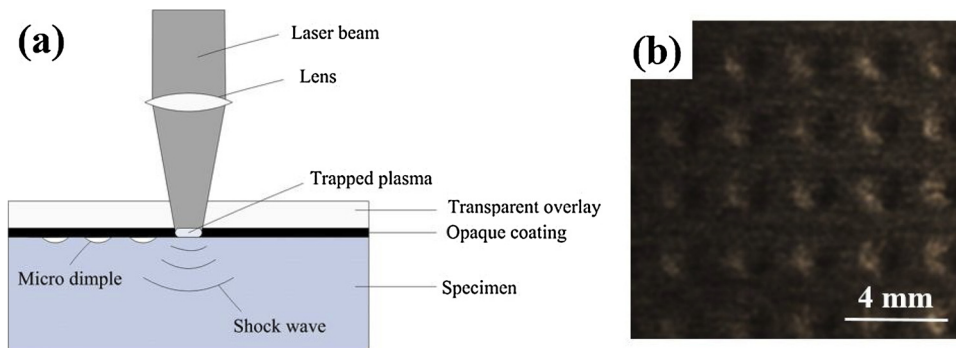


Fig. 4. (a) Schematic of LSP process and (b) surface dimples texture created by LSP [73].

showed the smoothest surface with sharpest dimple profile as compared to those processed by millisecond and nanosecond lasers. Ahuir-Torres et al. [87] compared surface morphologies of Ti6Al4V alloys as processed by ablation-based LST using nano-second and picosecond lasers. The authors found that the heat affected zone was significantly reduced by using picosecond laser instead of nano-second laser. A short pulse duration in laser ablation can minimize the undesirable thermal effect and increase the micro-structuring precision.

Table 2 illustrates a comparison of ablation-based LST techniques by different types of lasers in terms of the pattern geometry, costs, commercial availability and classes of materials. It can be seen that as compared to nanosecond and picosecond lasers, femtosecond laser holds the capability of fabricating higher quality surface features due to the reduced heat affected zone. However, the higher cost of femtosecond laser is a critical concern from a practical viewpoint.

3.2. Laser power intensity

Laser power intensity is one of the most important LST processing parameters determining the surface texturing effect. For LSP-based LST, the laser power intensity determines the shockwave pressure and

therefore the degree of plastic deformation during laser processing [89–92]. As a result, both the surface morphology and surface hardness of the processed samples are affected by the laser power intensity [70]. For ablation-based and interference-based LST processes, laser power intensity affects the amount of delivered laser energy, which determines the width, depth and shape of texture features as well as the area of heat affected zone.

Several studies have been carried out to investigate the effect of laser power intensity on the surface morphology and hardness of samples processed by LSP-based LST. For example, Sanchez-Santana et al. [76] showed that by increasing the laser power intensity from 900 to 5000 pu1/cm², the surface micro-hardness of a 6061-T6 aluminum alloy could be improved from 93 to 105 HV. As a result, the wear track depth decreased from 500 to 300 μ m after a sliding time of 3000 s. Guo et al. [93,94] investigated the effect of laser power density on the geometry of the surface feature generated by LSP-based LST. It was found that with the increase of laser intensity, the depth and diameter of the indentations increased as shown in Fig. 7. Moreover, a higher laser intensity leads to a more prominent surface roughening effect which affects the friction behavior.

For ablation-based LST, laser power intensity will strongly affect the

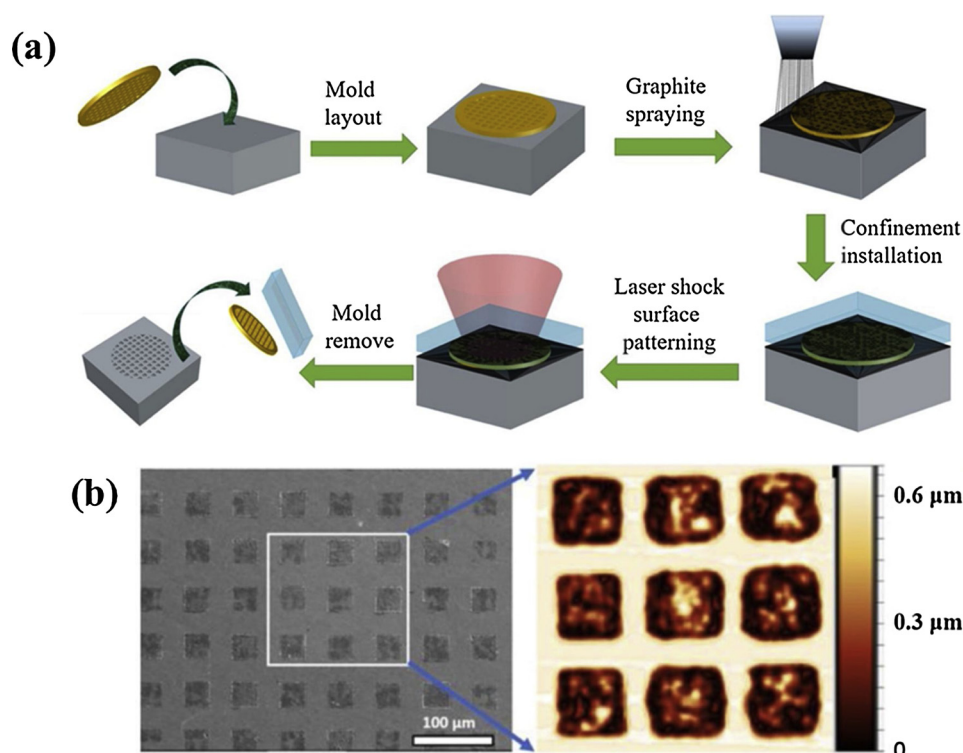


Fig. 5. (a) A schematic view of indirect-LSP process and (b) SEM and surface of profiles patterned micro-indentations [80].

Table 1

Comparison of LST techniques (The symbol ✓ denotes the degree. ✓✓✓✓✓ means very high and ✓ means very low).

Criteria	Laser ablation	Laser interference	Laser shock processing
Flexibility	✓✓✓✓	✓✓✓✓	✓✓✓
Efficiency	✓✓✓	✓✓✓✓✓	✓✓✓
Texture feature resolution limit	1 μm for titanium [81]	0.1 μm for silicon substrate [57]	10 μm for aluminum alloy [82]
Surface hardening effect mechanism	Heat induced phase transformation (only for some specific metals)	Heat induced phase transformation (only for some specific metals)	Surface plastic deformation for all metallic materials
Applicable materials	Metals, polymer, ceramics and composite materials	Metals, polymer, ceramics and composite materials	Only metals

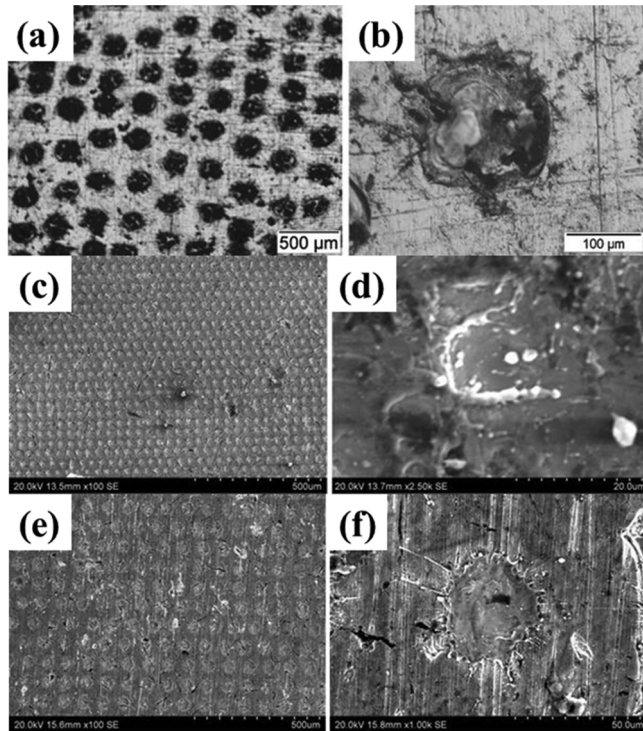


Fig. 6. Effect of laser type on the surface morphologies of gray cast iron as processed by ablation-based LST: (a) millisecond laser, (c) nanosecond laser, and (e) femtosecond laser; (b), (d), and (f) correspond to the enlarged area of individual dimple in (a), (c), (e) respectively [85].

Table 2

Comparison of ablation-based LST with respective to different types of laser, table adopted and modified from [88] and [6]. (ns = nanosecond laser, ps = picosecond laser, fs = femtosecond laser. The processing time estimates the time required to process an area of $100 \times 100 \text{ nm}$ with a feature width of $150 \mu\text{m}$ and a height of $20 \mu\text{m}$ and area coverage of 15 %).

Texture feature characteristics		ns	ps	fs
Geometry resolution	Width (μm)	10 μm	5 μm	$\leq 5 \mu\text{m}$
	Height (μm)	3 μm	1 μm	$\leq 1 \mu\text{m}$
Costs	Commercial	Yes	Yes	Yes
	Equipment cost	low	high	highest
	Processing cost	low	low	low
	Processing time	20 – 45 min	30s-several mins	30s-5min
Materials	Metals	Yes	Yes	Yes
	Ceramics	Only certain kinds of	Only certain kinds of	Yes
	Glass	Yes	Yes	Yes
	Polymers	Yes	Yes	Yes

geometry of the texture features in terms of depth and size. Dunn et al. [68] investigated the effect of laser parameters on the morphology of 314 stainless steels processed by ablation-based LST. The result showed that by increasing the laser pulse energy from 0.16 to 0.8 mJ, the dimple depth increased from 2 to 6 μm while the dimple diameter increases from 22 to 75 μm . Grabowski et al. [95] investigated the effect of laser power intensity on the laser-processed surface morphology of three metallic materials including AlSi7, Ti6Al4V alloy, and 316 L steels. It was found that the ablation depth almost increased linearly with the increase in laser power intensity for all three metallic materials (Fig. 8a). Moreover, the surface morphology of the ablated craters is well correlated to the distribution of the laser energy (Fig. 8b).

3.3. Number of laser pulses

In the LST processes, multiple pulses can be applied to manipulate the geometry of the surface features. It was also found that the number of pulses played an important role on determining the size, depth, and shape of the surface features. For instance, Yang et al. [96] investigated the effect of number of pulses on the ablation characteristic of bearing steel GCr15 as processed by LST. It was found that as the pulse number increased from 10 to 90, the radius of the texture feature increased from 12.72 to 13.37 μm . Vihena et al. [4] investigated the effect of number of pulses on the morphology of the micro-dimples fabricated on 100Cr6 steel by laser processing. The results showed that the depth, height, inner and outer diameter of the crater fabricated by laser ablation were strongly affected by the number of laser pulses. As shown in Fig. 9, with the increase of number of pulses, the height of the crater increased with a decrease of inner diameter.

4. Enhanced tribological performance of engineering materials by LST

With the understanding of how laser parameters enable design tribologically efficient LST surface textures, it is necessary to further discuss this knowledge to explain the mechanisms responsible for improved tribological behavior. In this section, the impact of texture design in defining the tribological performance of engineering materials is reviewed. The tribological performance is discussed in terms of manipulated surface textures by LST on COF and wear resistance under dry and lubricated conditions. The studies discussed in this section bridges the knowledge gap concerning the influence of LST design on the tribological properties.

4.1. Texture design

During the LST process, certain types of texture features are created on the surface of the targeted materials. Dimples and grooves are the main categories of texture features in LST. Fig. 10a shows the commonly observed texture features fabricated by LST. It is widely accepted that the tribological properties of the LST surfaces are strongly affected by the texture features, such as the shape [97], size [98], density [99], and arrangements [100], as schematically illustrated in Fig. 10b. For example, the texture density affects the real area of contact during dry

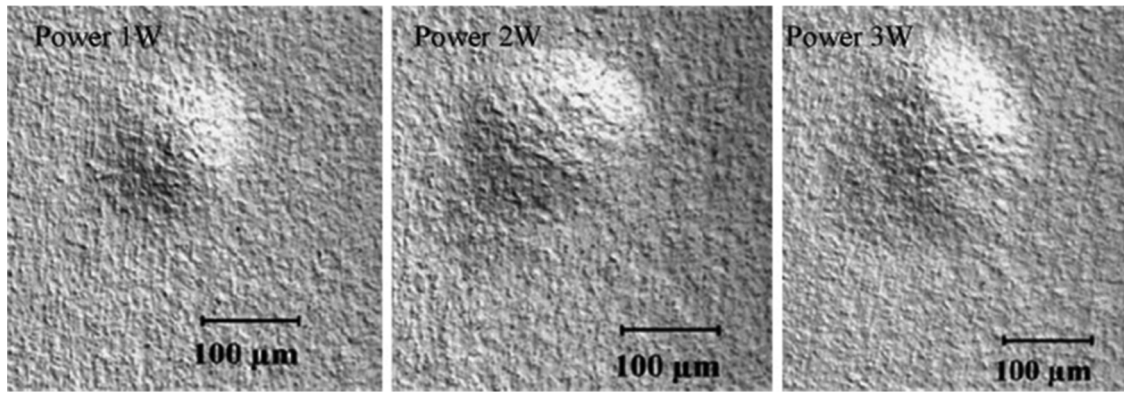


Fig. 7. Surface topography of samples processed by LSP with different laser intensities [94].

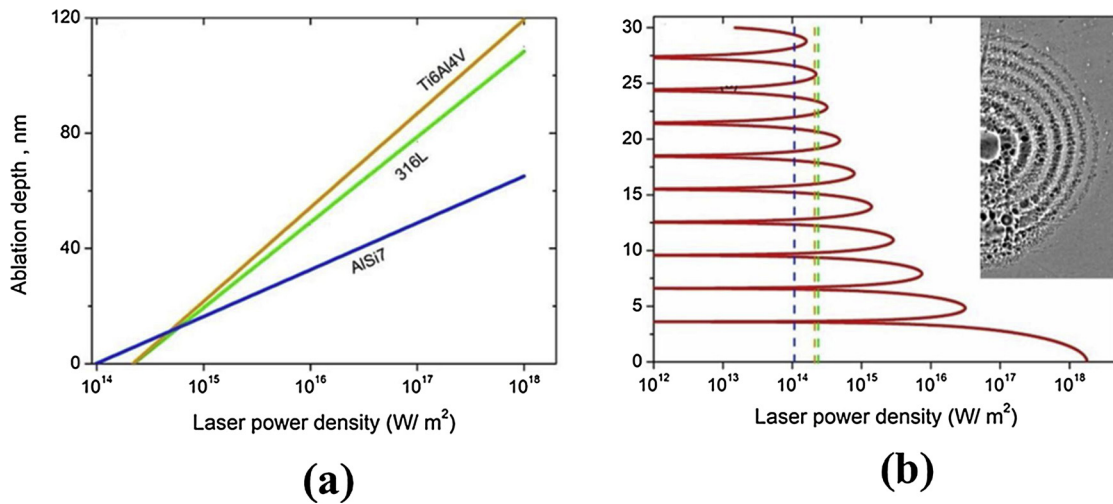


Fig. 8. (a) Variation of ablation depth with laser power density, (b) laser density profile for Airy diffraction texture (vertical dashed lines indicates the minimal densities of laser radiation that provide the ablation: blue - AISi7, orange - Ti6Al4V, green - 316 L [95] (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

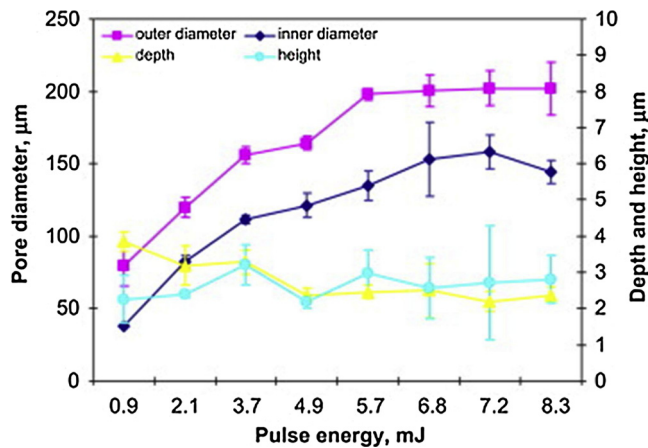


Fig. 9. Variation of the diameter, depth and height of the micropores fabricated by laser ablation as a function of the number of laser pulses (each pulse has an energy of 0.5 mJ) [4].

sliding contact and hydrodynamic pressure distribution during lubricated condition, as shown in Fig. 10c. Therefore, understanding the relationship between the texturing parameters and tribological properties is of particular interest for better designing of the LST process.

4.1.1. Texture feature fraction/ texture density

The texture feature fraction or density plays an important role on the tribological behavior of the LST processed surfaces. Under dry sliding conditions, the texture feature density affects the real area of contact as well as the trapping effect of wear particles at the sliding interface [101]. Under lubricated conditions, the texture feature density also affects the contact pressure distribution, and thus determines the form of lubrication as well as load bearing capacity of the LSP processed surfaces [102]. Schneider et al. [103] showed that there existed an optimal dimple density for reducing the COF of the C85 steels as processed by LST. A dimple density of 10 % was found to have the maximum reduction in frictional force. Similarly, Ezhilmaran et al. [67] showed that an optimal dimple density of 16 % on piston rings processed by LST greatly reduced the COF, while a high dimple density above 38 % was detrimental as the COF increased significantly with the increase in dimple density. Wu et al. [104] investigated the effect of density of the dimples on the tribological behavior of titanium alloys processed by LST. It was found that the distance between neighboring dimples remarkably influenced both the COF and the wear rates of titanium textured surfaces. Decreasing the distance between dimples, i.e., increasing the density of dimples, was beneficial to improve the anti-friction and anti-wear properties of the textured surfaces when filled with solid lubricants. Li et al. [105] studied the effect of texture feature density on the tribological behavior of AISI52100 bearing steels. Samples with a feature density of 5 %, 15 %, and 35 % (referred as T5, T15, and T35, respectively) were processed by LST. The SEM images of textured surfaces are shown in Fig. 11a-c. Sliding tests were carried out

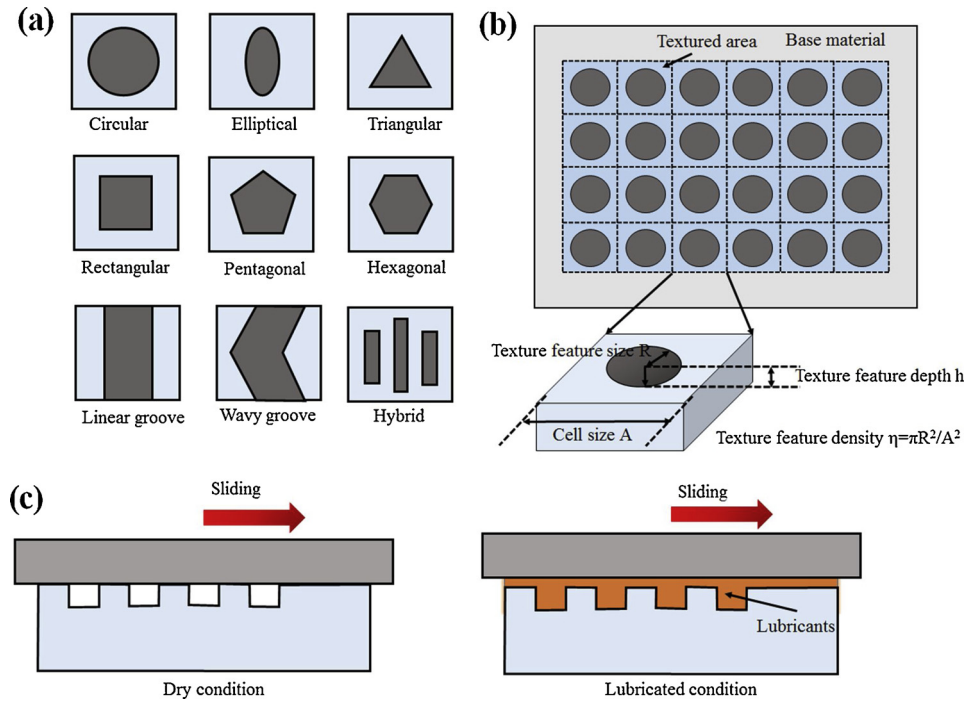


Fig. 10. Schematic illustration of (a) different kinds of texture feature shapes, (b) texturing parameters during LST process, and (c) the effect of texture design on the contact condition during dry and lubricated sliding.

in a ball-on-disk configuration in both dry condition and lubricated condition with a liquid metal (LM) lubricant. The wear rates of the balls corresponding to the untextured and textured surfaces with a sliding frequency of 10 and 2 Hz are shown in Fig. 11d and e, respectively. It can be seen that the texture feature density significantly affects the wear behavior. T15 has the highest anti-wear performance among all the textured surfaces in lubricated conditions.

For the surface texture composed of micro-grooves, the spacing between micro-grooves also play an important role on the tribological performance of the processed surfaces. Wang et al. [106] investigated the effect of groove density on the tribological properties of stainless steels processed by LST. Texture features with different groove

direction (Fig. 12) and spacing were fabricated on the surface of the samples. It was found that the COF decreased and then slightly increased with the groove spacing for the samples with both texture directions (Fig. 12e). Further, the COF was found to be higher for ST-45 when compared to ST-90 up to a critical groove spacing, beyond which the texture direction did not play a crucial role. This research indicated that the importance of groove spacing and direction in controlling the COF.

4.1.2. Texture feature size and depth

Apart from the fraction or density, the size and depth of texture features are also key parameters affecting the tribological performance

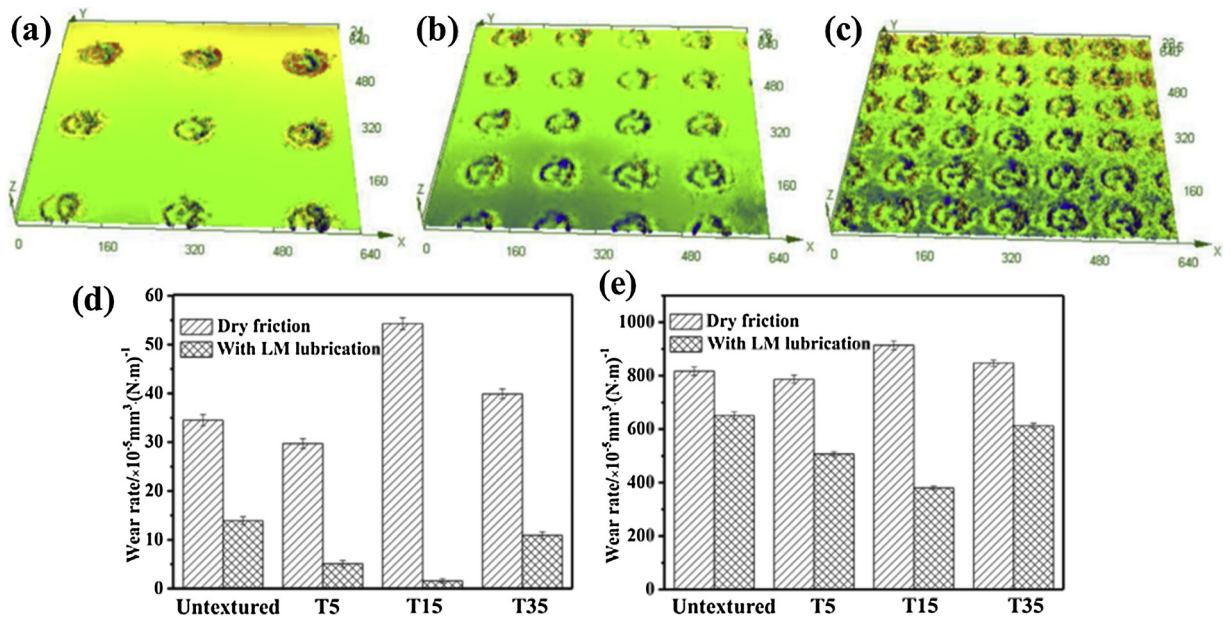


Fig. 11. SEM images of the surface morphology of AISI52100 bearing steels processed by LST with different texture feature density: (a) 5 %, (b) 15 % and (c) 35 %. Effect of texture feature density on the wear rates of the balls under sliding frequency of (d) 10 Hz and (e) 2 Hz [105].

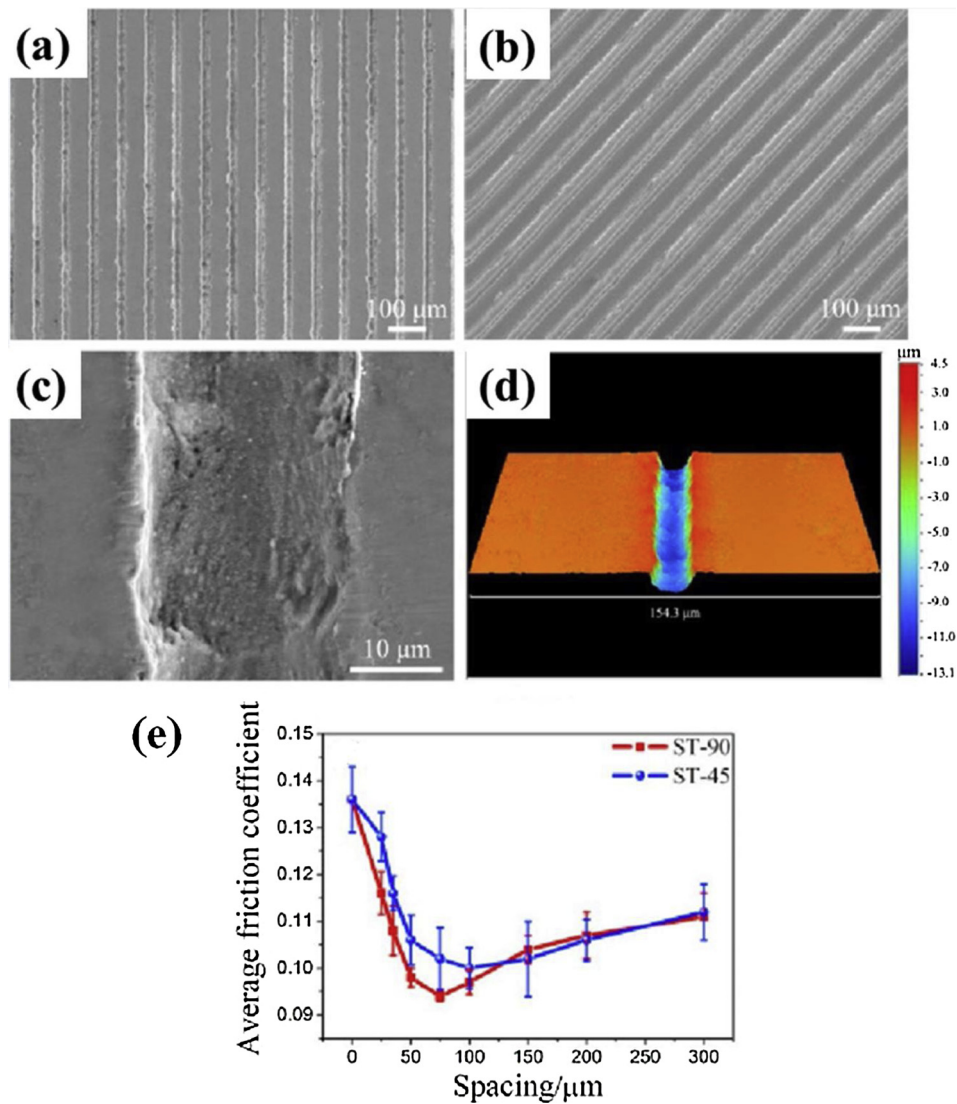


Fig. 12. SEM micrograph of the LST processed stainless steel with (a) 90° and (b) 45° micro-grooves. (c) Enlarged view corresponding to (a), (d) 3-D image of a single micro-groove, and (e) average COF of ST-90 and ST-45 with different micro-groove spacing, where ST-90 and ST-45 denotes the angles between sliding direction and groove direction are 90° and 45°, respectively [106].

of engineering components processed by LST. For instance, Boidi et al. [107] studied the texture feature depth of an AISI52100 steel processed by LST under lubricated condition. The results showed that shallow textures efficiently reduced the COF whereas deeper cavities brought detrimental effects. Greiner et al. [108] systematically studied the effect of dimple diameter and depth on the tribological behavior of a LST processed brass. For one set of samples, the dimple diameters were varied to be 20, 50, 75, 100, 150, and 200 μm with the dimple depth kept constant at 20 μm. To investigate the effect of the depth, samples with a constant dimple diameter of 50 μm but varied depths between 10 and 65 μm were fabricated. The surface SEM images of some samples with different dimple diameters are shown in Fig. 13a-c. The effects of dimple diameter and depth on the tribological properties are shown in Fig. 13d-e. It was observed that the static friction force decreased with the increase of dimple diameter for the LST processed samples (Fig. 13d). However, the static friction force firstly increased and then decreased with the increase of the dimple depth (Fig. 13e). The results in Fig. 13d-e indicate that there is a complex relationship between the friction behavior and texture feature geometry. A systematic study of the texture design in terms of feature size and depth is often necessary for better tribological performance.

Further, it should be noted that the optimal design of surface feature

depends on the operating conditions. Braun et al. [109] investigated the effect of texture morphology on the tribological properties of 100Cr6 steel and showed that the optimal dimple diameter under lubricated condition was 40 μm at an operating temperature of 100 °C. While it was 200 μm at 50 °C.

4.1.3. Texture feature alignment

The alignment of surface texture features is also found to have significant impact on the tribological performance of materials processed by LST. The relative orientation between the patterns and sliding directions will affect the frictional forces during sliding and therefore affect the tribological performance [110]. For example, for sliding on unidirectional surfaces, the interactions between asperities are expected to be different based on the sliding directions, leading to the so called “friction anisotropy” [111]. Xing et al. [112] investigated the effects of texture alignment on the ceramic surface processed by LST under dry condition. Three surfaces with different alignment of texture features, smooth surface (AS), linear grooves (AT-L) (Fig. 14b), and wavy grooves (AT-W) (Fig. 14c) were fabricated. The COF during pin-on-disk tests as affected by the texture feature alignment is shown in Fig. 14d. It was shown that the surface with a smooth surface exhibits the lowest COF, while the surface with a wavy grooves has the highest COF under

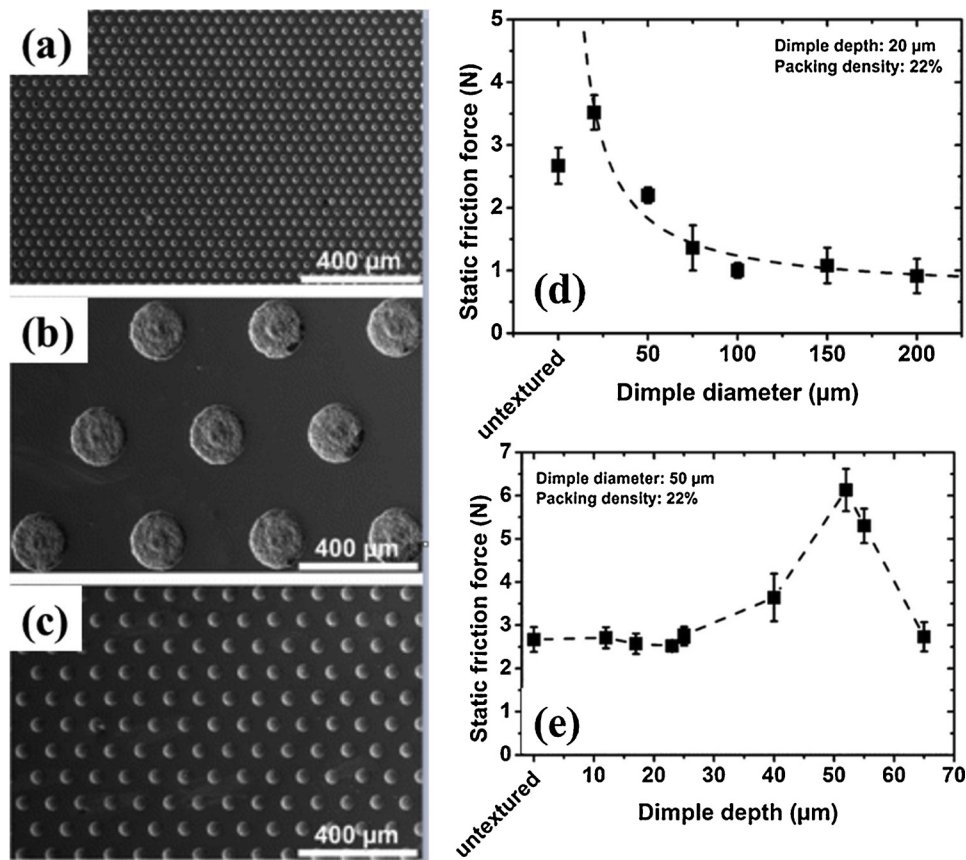


Fig. 13. SEM images of LST processed brass samples with different circular dimples with a diameter of (a) 20 μm, (b) 200 μm, and (c) 50 μm; (d) static friction as a function of dimple diameter for a dimple depth of 20 μm and (e) static friction as a function of dimple depth for a dimple diameter of 50 μm [108].

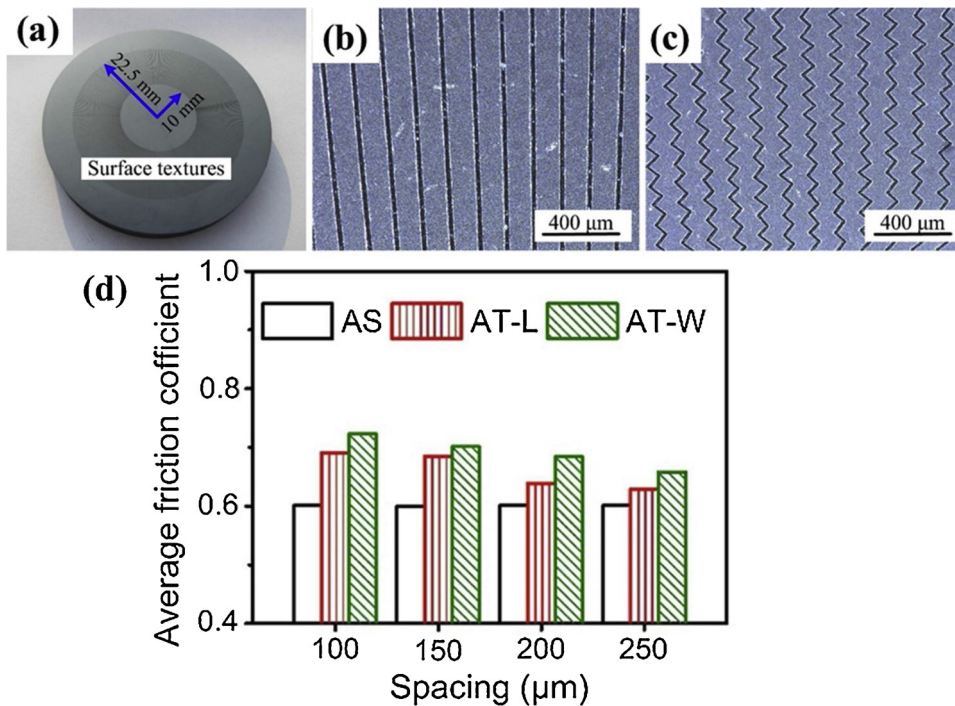


Fig. 14. (a) Optical images of the textured ceramic disk, (b) linear grooves, (c) wavy grooves, and (d) variation of average COF of smooth and textured samples with different loads under dry sliding for a sliding speed of 80 m/min [112].

all loading conditions.

4.1.4. Texture feature shape

With the advances of LST techniques, surface texture with various shapes, such as circle, sphere, ellipse, triangle, and bio-inspired pattern have been developed and studied in recent years. The shapes of the texture feature proved to have a significant impact on the tribological properties of materials processed by LST. For instance, Yu et al. [113] reported that a surface with an elliptical texture or a triangle texture has smaller load-carrying capacity as compared to the circular dimple texture under the condition of having the same feature size and depth. Sedlacek et al. [114] investigated the effects of shapes of the texturing features on the tribological performance of P/M tool steels and found that texture features with a pyramidal shape resulted in the highest COF, even higher than that for untextured surface.

4.2. Manipulated COF by LST

Controlling COF in an engineering application is important in defining the overall tribological performance of the system [115]. It is generally accepted that COF of a tribo-pair can be considered to be the combination of adhesion component and plowing component [116–118]. The adhesion component depends on the material pair, the real area of contact, and lubrication condition. Whereas, the plowing component depends on the degree of plastic deformation taking place at the asperity level [5,119]. During LST, by controlling the surface micro-features, such as the geometry of the textures, it is possible to manipulate the COF [120].

4.2.1. Dry condition

Extensive research has been carried out to investigate the effect of LST on the COF in dry condition. A detailed review of the recent studies is summarized in Table 3. It is typically assumed that LST can lead to lower the COF due to the reduction of real area of contact. For instance, Rosenkranz et al. [121] showed that the COF of stainless steels can be reduced by 50 % after processed by LST. Gualtieri et al. [122] reported that the COF of a nitride steel decreased from 0.08 for the untextured surface to 0.05 for the surface processed by LST. However, this study reveals that the reduction in COF not only due to the surface texturing effect but also due to the surface hardening effect attributed to grain size reduction induced by laser heating. Borghi et al. [123] investigated the friction and wear behavior of 30NiCrMo12 nitride steel as processed by LST under dry condition. Regular arrays of circular dimples with a diameter of 100 μm , a depth of 50 μm , and a surface density of 40 % were fabricated on the surface of the samples, as shown in Fig. 15a–b. Fig. 15c shows the evolution of COF for the textured and untextured surfaces during sliding under dry condition at a normal load of 1 N and a sliding speed of 12 cm/s. It was observed that the COF was reduced by 15 % due to LST.

It is evident that the LST techniques can be utilized to reduce the COF for better tribological performance. However, under some

circumstances, such as metal forming process, the COF needs to be manipulated to obtain the required stresses at tribo-pair interface [124–126]. In this regard, LST was applied to define and tailor specific tribological performances for engineering structures. For instance, Mao et al. [80] developed an indirect-LSSP method to process an AISI 1045 steel. The effects of laser intensity on the texture indentation depth and its influence on COF is shown in Fig. 16a and b, respectively. It was found that by increasing the laser intensity, the depth of the indentation increased as a function of shockwave peak pressure. However, the COF dropped from 0.38 for the untreated sample to 0.15 for the sample processed with a laser intensity of 0.484 GW/cm², and then gradually increased with the increase of laser intensity due to the surface roughening effect (Fig. 16b). Similar trend was also observed in their research carried out on an AZ31B Mg alloy [127], in which direct-LSSP was performed. It was found the combined effect of surface texturing and hardening effect was responsible for the change of surface COF.

4.2.2. Lubricated condition

Considerable amount of research show that the surfaces processed by LST exhibit a lower COF under lubricated conditions [130]. For instance, Wan et al. [131] showed that the COF was reduced from 0.42 to 0.12 on a T8 steel. These steel surfaces had micropores with a diameter of 200 μm and a depth of 10 μm through LST. The micropores decreased the contact area, helped to trap wear debris and thus to decrease plowing, and act as a lubricant reservoir. Kovalchenko et al. [132] demonstrated that the LST can facilitate transition of lubricated contact, from the high-friction boundary regime to the lower friction mixed regime. Significant COF reduction by LST with solid lubricants was also realized on some hard materials like WC/Co cemented carbide, as evidenced by the research carried out by Ze et al. [133]. By creating micro-grooves on the cemented carbide substrate, the surface COF of the textured samples was reduced by 30–35 % compared with that of un-textured samples. Under lubricated condition, some researchers also found that LST was helpful on stabilizing the surface COF and made it less dependent on the kinds of lubricants during sliding tests. For instance, Wos et al. [134] showed that LST could significantly reduce the scatter of COF by with different lubricants due to the generation of hydrodynamic lift by the dimples created by LST.

A detailed illustration of the recent studies concerning the effect of LST on the COF of different materials under lubricated condition is summarized in Table 4. It can be seen that the COF before LST are higher than they are after LST in most of the cases. The mechanisms responsible for the reduced COF by surface texturing under lubricated condition include: (1) the texture features promotes the early transition to hydrodynamic lubrication, (2) the reserved flow generates cavitation lift force, and (3) the surface wedge forms or imbeds into the dimples [101]. It must be noted that the COF is always a system property which is determined by the specific tribo-pairs and testing environment. The results in Tables 3 and 4 may be just valid under the certain circumstance in the respective references. However, Tables 3 and 4 show that LST has the capability to manipulate the surface COF in

Table 3

A summary of recent research on the effect of LST techniques on the COF of different materials during sliding tests under dry conditions.

Material	LST method	Texture design	Effect on COF	References
Ni-based composite	Laser ablation	Circular dimples	Reduced by 50 %	[128]
Nitride steel	Laser ablation	Circular dimples	Reduced by 37.5 %	[122]
Stainless steel	Laser interference	Linear grooves	Reduced by 50 %	[121]
Cast iron	Laser ablation	Circular dimple	Reduced by 57.9 %	[129]
Al ₂ O ₃ /TiC composite	Laser ablation	Linear grooves	Reduced by 16.7 %	[112]
Ti-6Al-4V	Laser ablation	Circular dimples	Reduced by 40 %	[104]
304 stainless steels	Laser ablation	Circular dimples	Increased by 272.3 %	[68]
AISI 1045 steels	LSP	Square dimples	Reduced by 34.2 %	[80]
100 Cr steel	LSP	Circular dimples	Reduced by 18.2 %	[77]
Al 6061 alloy	LSP	Circular dimples	Reduced by 18.2 %	[76]

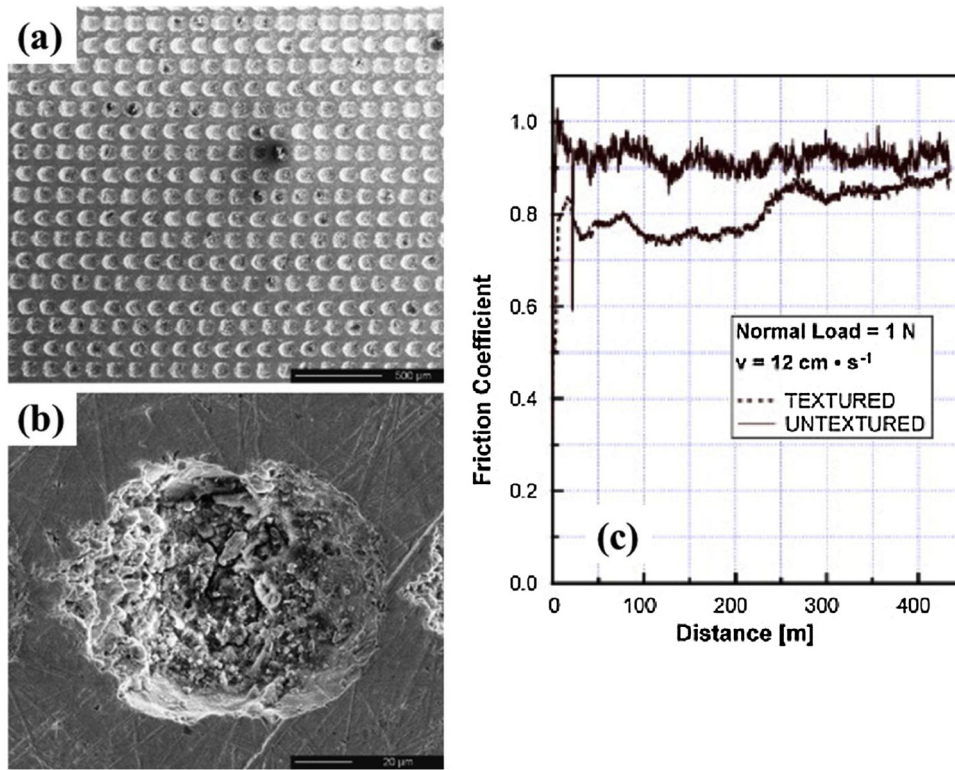


Fig. 15. (a) SEM image of 30NiCrMo12 nitride steel as processed by LST, (b) SEM image of an individual dimple, and (c) variation of COF with sliding distance of untextured and textured surfaces in dry conditions [123].

a wide range both in dry and lubricated conditions.

Moreover, some researchers found that an optimal surface texture is also required for reducing the COF under lubricated condition. For instance, Tripathi et al. [31] investigated the effect of LST on the COF of grey cast iron under two different lubricants with high and low viscosity. The variation of COF for the untextured and textured samples with different dimple density under low and high viscous lubricants are shown in Fig. 17a and b, respectively. Under the two lubricated conditions, it can be observed that the textured surface with a dimple density of 22 %, 10 %, and 5 % can significantly reduce the COF as compared with the untextured surface. However, as the dimple density increases to 35 %, the COF increases and eventually exceeds the values for those of the untextured surface.

4.3. Improved wear resistance by LST

Wear resistance is another important factor in the tribological applications of engineering materials. It determines durability and product quality of engineering components. Improving the wear resistance of engineering materials by LST have been realized on a variety of applications in both dry condition and lubricated conditions.

4.3.1. Dry condition

LST can be great beneficial to improve the surface wear resistance of metallic materials either by increasing the surface hardness or decreasing the contacting area [137,138]. For instance, Hussein et al. [63] showed that the wear rate of aluminum alloys can be reduced by 7 time after processing by LST as a result of the combined surface hardening

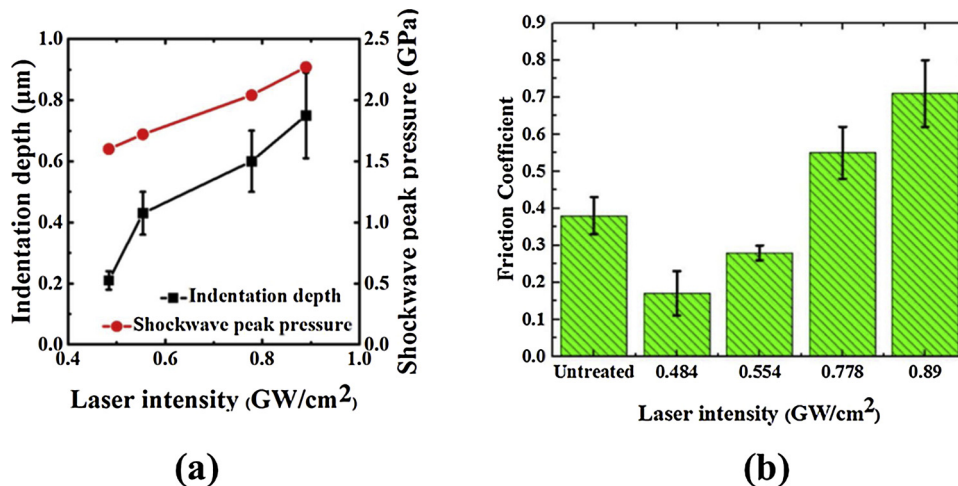


Fig. 16. (a) Variation of indentation depth with laser intensity during the LST experiments of AISI 1045 steels and (b) variation of COF with laser intensity during sliding tests in dry conditions [80].

Table 4

A summary of recent research on the effect of LST techniques on the COF of different materials during sliding tests under lubricated conditions.

Material	LST method	Texture design	Lubricant used	Effect on COF	References
Stainless steel	Under water laser ablation	Circular dimple	Mobil 1045 lubricant	Increased by 400 %	[45]
Grey cast iron	Laser ablation	Rectangular dimple	poly-alpha-olefin oil	Reduced by 60 %	[135]
T8 steel	Laser ablation	Circular dimple	Smeared oil	Reduced by 80.1 %	[131]
100Cr6 steel	Laser ablation	Circular dimples	poly-alpha-olefin	Reduced by 60 %	[109]
Cemented carbide	Laser ablation	Linear grooves	Liquid drops (not specified)	Reduced by 46.1 %	[136]
Copper	LSP	Circular dimples	Mobil Vacuoline 1405	Reduced by 50 %	[73]
Ti6Al4V alloy	LSP	Circular dimples	30# Oil	Increased by 3.6 %	[78]

and surface texturing. Wu et al. [104] investigated the tribological properties of dimple-textured titanium alloys under dry sliding condition. The 3D topographies and 2D cross-section profiles of worn scars of the unprocessed and LST processed titanium surfaces are shown in Fig. 18a and b, respectively. It can be seen that both the width and depth of the worn scar for the LST processed surface were smaller than those of the unprocessed samples, indicating a better wear resistance that is achieved by LST.

LST can be also utilized to improve the wear resistance of some metallic materials at high temperature where the liquid lubricants cannot be used, thus providing tribological solutions for mechanical components working at severe environment. Sun et al. [139] showed that the wear resistance of a TC11 alloy working at 500 °C can be significantly improved by LST. A schematic illustration of the wear mechanisms of the textured and untextured surfaces was proposed and shown in Fig. 19. The texture feature fabricated by LST can act as wear debris traps which could avoid the abrasive wear caused by wear debris. Moreover, some micro-textures with a dense dimpled structure is likely to form and providing a higher anti-wear effect. Furthermore, as the TC11 alloy is exposed in air at 500°C, the contacting surface reacts with the oxygen in air and forms a layer of titanium oxide with a high hardness and load-bearing capacity. The textured surface allows the formation of larger amount of tribo-oxides as compared with those on the untextured surface. Therefore, a remarkable increase of wear resistance of TC11 alloy is obtained by LST.

4.3.2. Lubricated condition

The effective and enhanced lubrication is always in demand to meet the increasingly stringent operational conditions of mechanical components. The micro dimples or grooves fabricated by LST can serve as fluid reservoirs which effectively retain the lubricant [31,136,140]. Entrapped lubricant will act as micro-bearings sustaining the load and thus extend the life of mechanical components. In some circumstances, micro-dents may also function as traps for wear debris, eliminating a

potential plowing effect caused by entrapped wear debris [141]. Moreover, Kümmel et al. [142] recently demonstrated that the adhesive wear of Ti6Al4V alloys were significantly prevented by LST processing due to the lowered chemical activity of melt bulges formed by LST. Therefore, LST can greatly improve the wear resistance of metallic materials and some researchers even demonstrated that LST can improve the surface lifetime by a factor of ten [140,143,144]. Li et al. [128] investigated the effect of LST on the tribological performance of nickel-based composite with MoS₂ powders as solid lubricant. The results showed that the micro-dimples fabricated by laser ablation could store MoS₂ powders as well as trapped wear debris. The wear life of composite was significantly extended by laser surface texturing. Moreover, the effective lubricating temperature of MoS₂ was increased to about 500 °C with the help of LST, while it was about 300 °C for the samples without LST processing. A mechanism responsible for the enhanced wear resistance in lubricated condition has been proposed by Hao et al. [136]. In their study, an oleophobic micro-textured surface was fabricated on a cemented carbide by LST and showed significant tribological property enhancement. As shown in Fig. 20b, compared with the untextured surface (Fig. 20a), the oleophobic textured surface can store lubricant for the friction pair interface. Moreover, the oleophobic property the texture feature can promote the lubricants accumulate toward the friction pair interface, which further help to improve the lubricating conditions on the friction pair interface.

Similar research was carried out by Rosenkranz et al. [140]. In their research, the oil film lifetime and worn surface of stainless steels processed by LST were analyzed. Two types of LST processed surface with a neighboring pattern distance of 6 and 9 μm were fabricated. Fig. 20a and b show the worn surface after 20 % of the maximum oil film lifetime. Fig. 21c and d shows the surface topography of the worn surface after the maximum oil film lifetime. From Fig. 21a and b, it can be observed that the surface features were partially degraded and some abrasive wear scars were generated. However, despite these wear features, the cross-like patterns still existed for both the surfaces processed

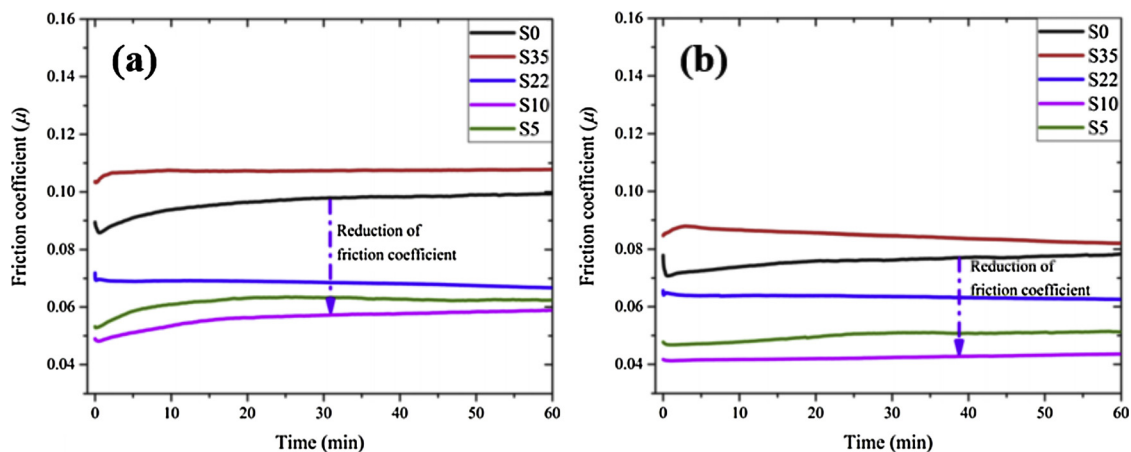


Fig. 17. Variation of the COF of the untextured and textured grey cast iron under (a) low viscous lubricants and (b) high viscous lubricants, samples marked as S0, S35, S22, S10, and S5 represent the samples with a dimple density of 0 % (untextured), 35 %, 22 %, 10 %, and 5 % respectively [31].

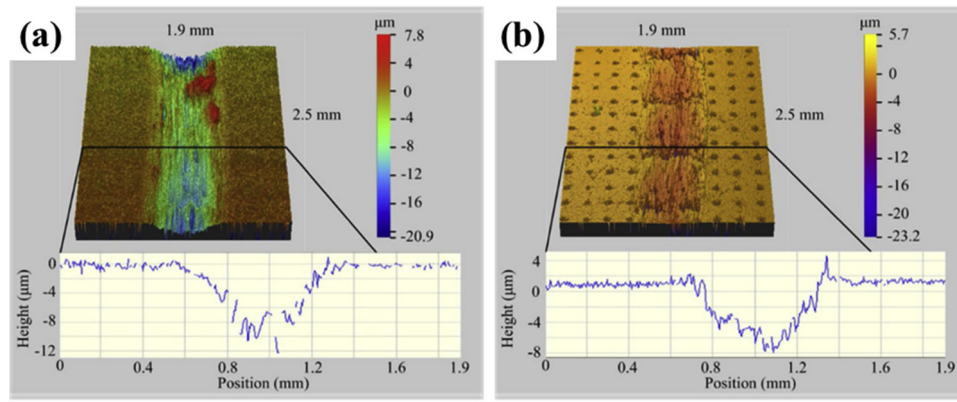


Fig. 18. The 3D topographies and 2D cross-section profiles of worn scars on two different kinds of titanium samples after 5 min sliding time with the speed of 25 m/min and 8 N load: (a) untreated surface, (b) dimple patterns with dimple distance of 200 μm [104].

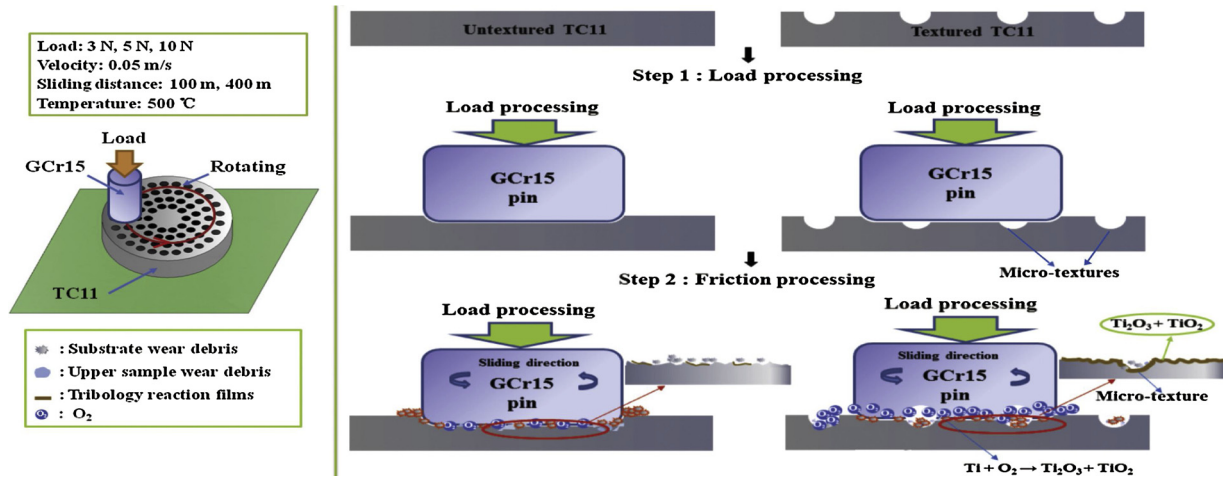


Fig. 19. Schematic illustration of the effect of LST on the wear mechanism of TC11 alloy tested at 500 °C [139].

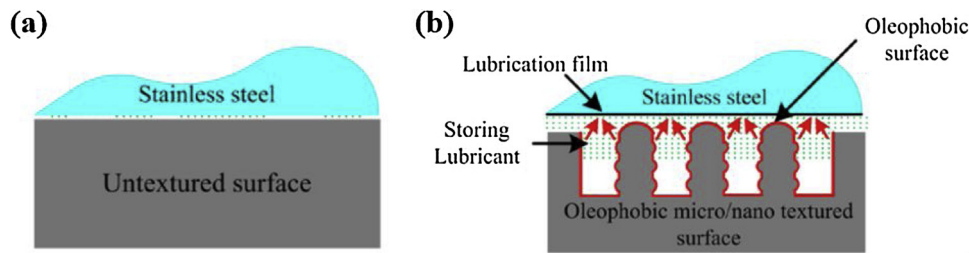


Fig. 20. Schematic illustration of the lubricating mechanisms on the (a) untextured and (b) oleophobic textured surface of a cemented carbide processed by LST [136].

by LST, which allows for further storage of oil and wear particles during sliding.

5. Applications

LST has been widely employed in various applications for improving their tribological performance [145,146]. As shown in Fig. 22, it has been used in mechanical components like gears and cutting tools, bio-implant products like dental implants and knee replacements, and electronic devices like magnetic disk. This section reviews state-of-the-arts of the applications of LST. Particular focus will be made in three specific areas, mechanical components, bio-implants, and electronics devices.

5.1. Mechanical components

The knowledge of LST originated from the motivation of realizing better tribological performance of the mechanical components in engine. Therefore, extensive studies of LST have been carried out on mechanical components, such as mechanical seals [26], thrust bearings [27], piston rings [28]. Table 5 summarized some classical examples of the applications of LST on the mechanical components. It can be concluded that LST can effectively reduce the COF of the surfaces of various mechanical components and improve their wear resistance. For example, in the research carried out by Xing et al. [147], the rake faces of a $\text{Al}_2\text{O}_3/\text{TiC}$ ceramic tools were processed by LST and their tribological performance was studied. Three different textures were fabricated on the rake face of the cutting tools. These textures are AT-PE which represents a texture with linear grooves perpendicular to the cutting edge

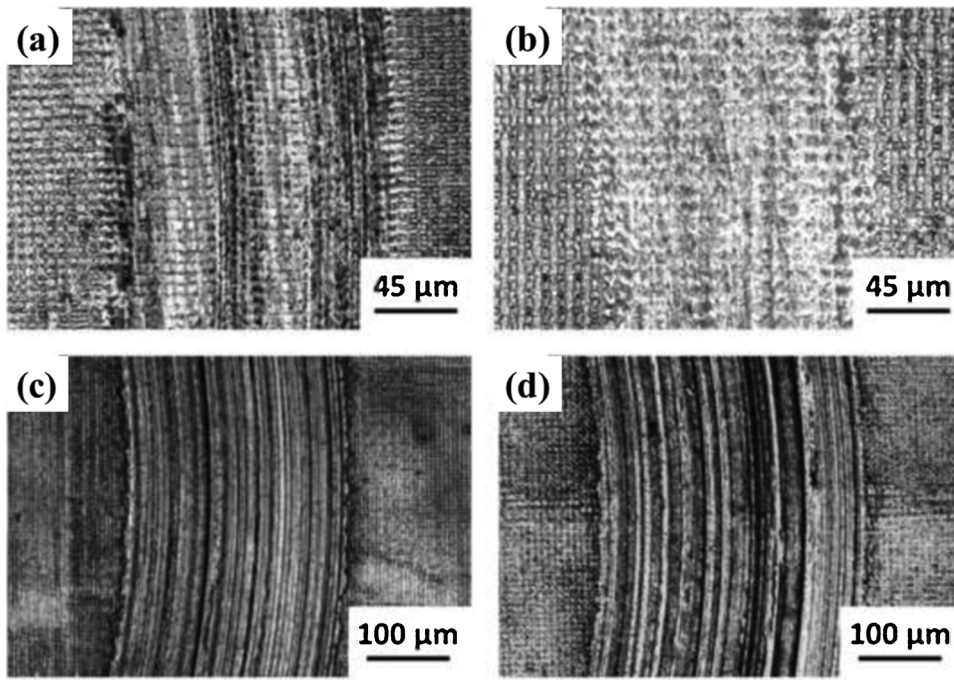


Fig. 21. Worn surface topography of the samples processed by LST with a structural wavelength of 6 (a) and 9 μm (b) after 20 % of the maximum oil film lifetime of the respective wavelength (approximately 25,000 and 10,000 cycles for a structural wavelength of 6 and 9 mm, respectively). (c) and (d) features of the worn surface after the maximum oil film lifetime for 6 and 9 mm, respectively [140].

(Fig. 23a), AT-PA which are textures with linear grooves parallel to the cutting edge, and AT-W which is a texture with wavy grooves. Cutting tests were carried out under lubricated conditions and the COF for the cutting tools processed by LST in different cutting speed was shown in Fig. 23b. It was found that the textured surfaces exhibited a lowered COF compared with the untreated counterpart (AS in Fig. 23b). Worn surfaces after cutting operation were examined by energy dispersive spectroscopy, as shown in Fig. 23c-f. It can be seen that the tool wear was significantly reduced by LST. The enhanced wear resistance of the cutting tools was attributed to the lubrication effect due to microscale textures, and the formation of a lubricated film at the tool-chip

interface.

5.2. Bio-implants

Besides the applications on mechanical components, LST has been utilized to improve the tribological performance of bio-implants, such as artificial joints and dental implants in which friction and wear will increase over time and finally result in the failure of these implants [24]. The successful practice of LST on bio-implants can be found in titanium and its alloys which are among the most widely used bio-implant materials due to their high strength to weight ratio, good

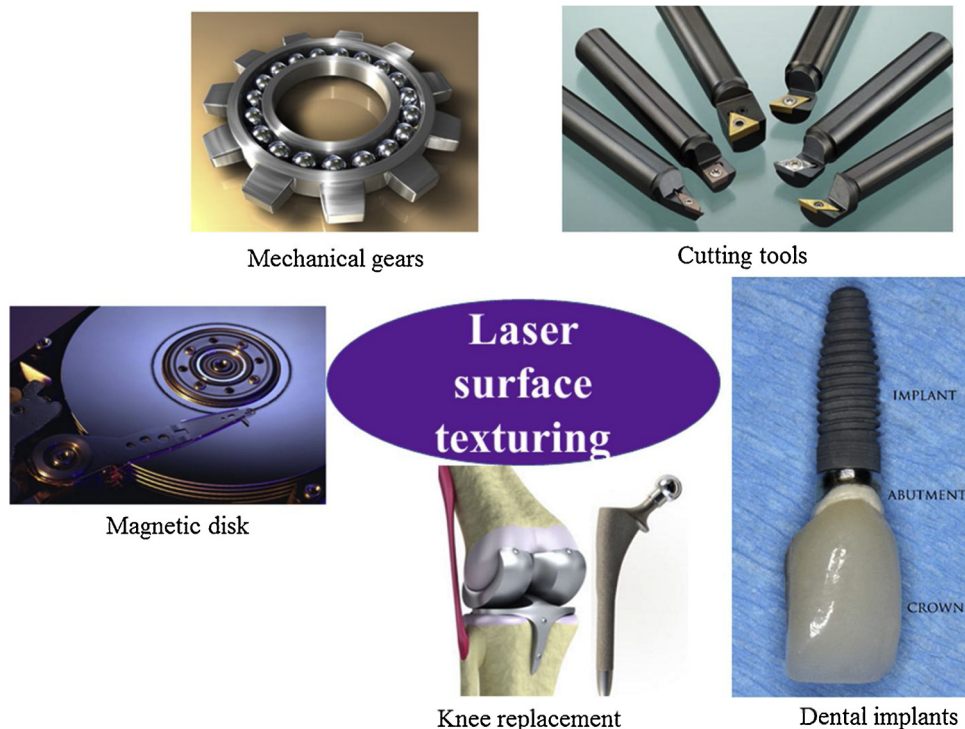


Fig. 22. Examples of LST applications.

Table 5
Applications of LST on the different mechanical components.

Mechanical components	Materials	LST method	Effect on COF	Effect on wear resistance	References
Piston rings	Casted iron	Laser ablation	Reduced by 20–35 %	No detailed data	[148]
Piston rings	Moly-chrome coating	Laser ablation	Reduced by 76 %	Significant increase	[67]
Mechanical seals	Tungsten carbon	Laser ablation	Reduced by 60 %	No detailed data	[26]
Thrust bearings	Silicon carbide	Laser ablation	Reduced by 75 %	Increased 3 times	[96,149]
Rolling bearings	Silicon carbide	Laser ablation	Reduced by 30 %	No detailed data	[150]
Rolling bearings	Al-Sn-Si alloy	Laser ablation	Reduced by 20 %	No significant difference	[151]
Injection cam	Steels	Laser ablation	Reduced by 10 %	No detailed data	[66]
Facing seal	T8 steels	Laser ablation	Reduced by 70 %	Increased by 10 times	[131]
Cutting tool	Al ₂ O ₃ /TiC ceramics	Laser ablation	Reduced by 18 %	Significant increase	[147]

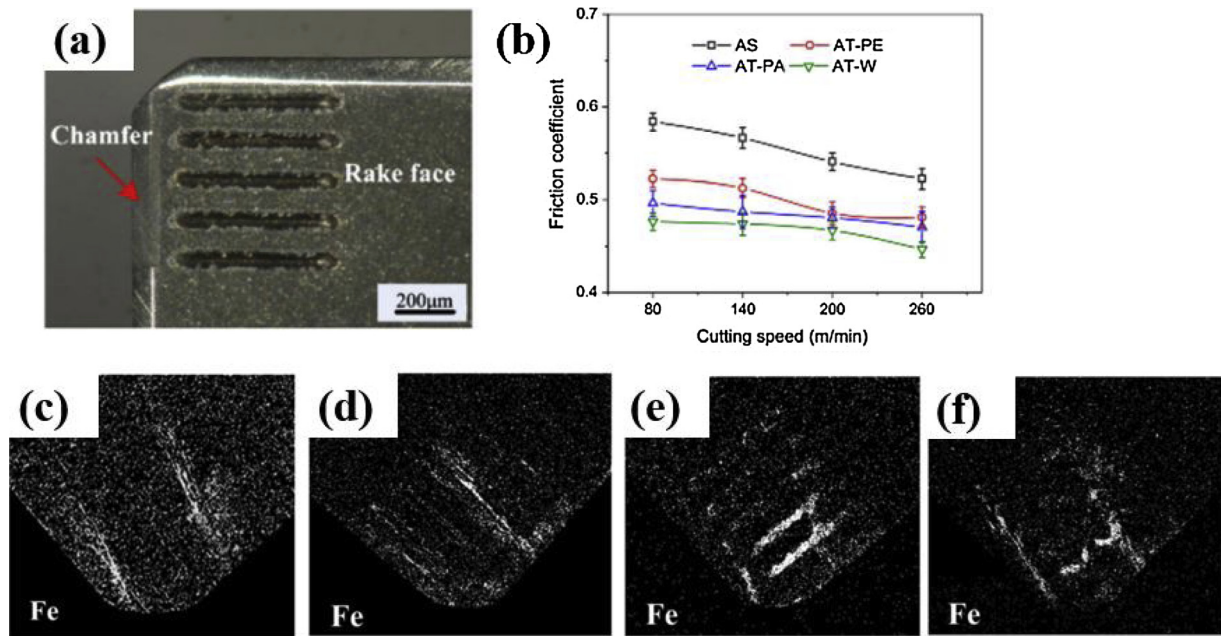


Fig. 23. (a) Optical micrograph of the rake face by LST; (b) variation of COF at the tool-chip interface with cutting speed for four kinds of tools, AS, AT-PE, AT-PA, and AT-W represents the surface without LST, with linear grooves perpendicular to the cutting edge, with linear grooves parallel to the cutting edge, and with wavy grooves, respectively; (c–f) energy dispersive spectroscopy analysis of the worn surface after cutting tests for the AS, AT-PE, AT-PA and AT-W tools [147].

corrosion resistance and excellent bio-compatibility [152]. In recent years, LST technology has been utilized to improve their tribological properties [153–155]. For example, Hu et al. [154] showed that the COF of a Ti6Al4V alloy can be reduced from 0.7 to 0.1 under lubricated condition after LST processing. Another example was reported by Kumari et al. [156,157] where surface textures with linear grooves and round dimples on Ti6Al4V alloy were fabricated by laser ablation as shown in Fig. 24a and b. The variations of COF with sliding time for the surface with and without LST are shown in Fig. 24c. It can be observed that for the unprocessed surface, the COF increased up to 1.0 and then fluctuated in the range of 1.0–1.4 with sliding time. While for the textured surface, the COF was around 0.4 for 1500s and then slightly increases up to 0.5–0.66. This study shows that the LST could efficiently reduce the COF of Ti-6Al-4 V alloy, which enables its better tribological performance in bio-implant materials.

5.3. Electronic devices

In some electronic devices, such as magnetic tape drives, tribological performance of the tape is often an important issue since the COF determines the torque required from the motor, and the wear determines the quality of the tape. LST has been utilized to enhance the tribological properties of tape in the magnetic drives and has shown promising results [29,158]. For instance, in the research carried out by Raeymaekers et al. [158], an experimental set up simulated the moving

of a tape on a stationary guide is shown in Fig. 25a. The variation of COF with sliding speed under different tribo-pairs is shown in Fig. 25b. It can be seen that the metal evaporated tape processed by LST (LST/MP) exhibited the lowest COF values. Since LST can also reduce the influence of speed on the COF, this aspect of LST will be beneficial for the overall performance of the tape drive.

6. Challenges and future directions

Although LST and related processes have been proven to be efficient in enhancing the tribological performance of engineering materials, these techniques need to be optimized to produce precise surface textures in terms of geometry and feature sizes with good homogeneity. Moreover, the process scalability and cost are other concerns in order to be integrated into manufacturing systems [6]. In this regard, the use of LST techniques on enhancing the tribological performance of engineering materials should entail an optimization process in terms of contact configuration, dimple parameters, and selection of appropriate tribo-pair. This section reviews the current challenges and the future research directions of LST towards tribo-applications.

6.1. Current challenges

6.1.1. Texture design

Although tremendous research efforts have been made to explore

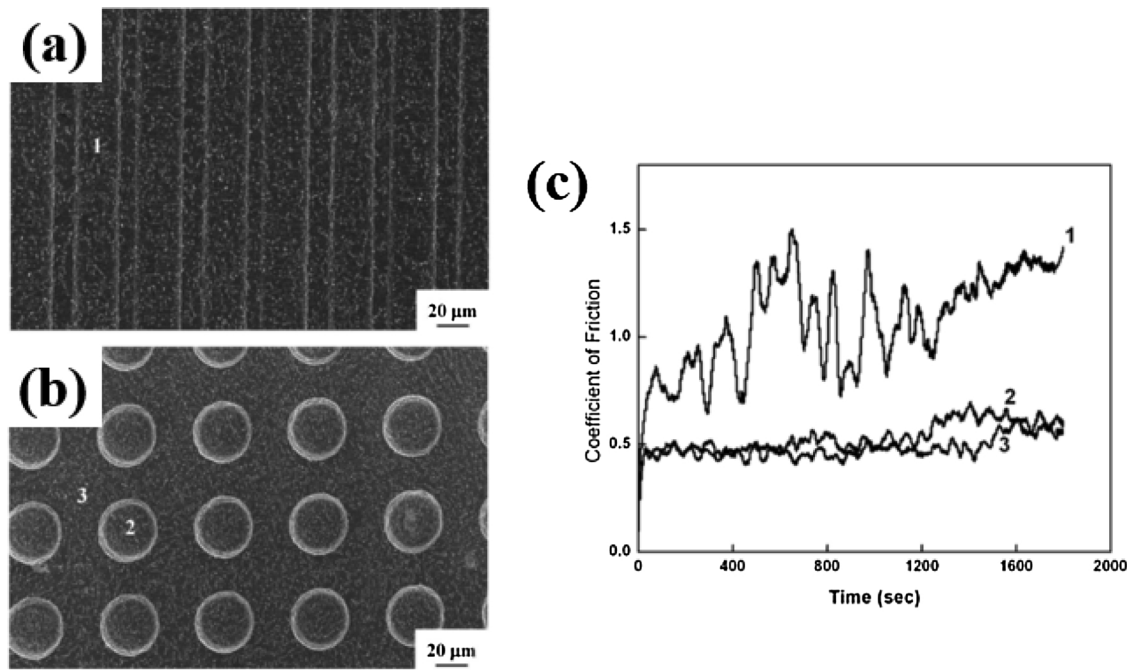


Fig. 24. SEM images of the surface morphologies of Ti6Al4V alloy processed by LST with (a) linear texture geometry and (b) dimple texture geometry; (c) variation of COF with sliding time for the surface without LST processing (line 1), with linear geometry (line 2) and dimple geometry (line 3) processed by LST [157].

the optimal texture design for enhancing the tribological properties of engineering materials by LST, there still lacks a standard or a criteria for guiding the design of surface textures. Since the tribological performance of a system depends on a variety of factors, such as the mechanical properties of the tribo-pairs [159], loading conditions [160], and the environmental parameters [161], optimization of the texture design normally lacks the general guideline but rather relies on a case-by-case experimental study. The complexity of the relationship between surface texture and tribological properties along with the mechanical properties and microstructure evolution during the LST process has raised a great challenge for the optimal texture design.

6.1.2. Texture wear resistance

The materials processed by LST are always subjected to degradation and wear in their practical applications. Once the texture features are worn out, their enhancement on the tribological properties is lost. Therefore, maintaining the texture features, in other words, improving their wear resistance is of critical importance for the durability and reliability of engineering components processed by LST.

6.2. Future directions

6.2.1. Computational methods

Computational or numerical modeling might be a substitute to the expensive experimental studies for the LST process optimization. Robust numerical models allow the evaluation of the texture design before manufacturing processes and thus can avoid time consuming experimental trial and error approaches [162]. Numerical models developed in recent studies [163–165] are capable to predict the transient effects, temperature affect, pressure distribution, asperity contact and deformation in various sliding cases. For instance, Zhou et al. [166] proposed a theoretical model for optimal design of surface texturing on cylinder liner based on a specific operation condition of cylinder liner and piston ring of CY6102 diesel engine. They took the Reynolds equation [167] to calculate the hydrodynamic pressure distribution over a single micro-pore and then got the relationship between the dimensionless film pressure with the depth over diameter ratio and are density. The result showed that an optimum texturing design existed and the optimum densities were 16–22 %, 14–18 %, and 10–12 % in low, medium and high velocity ranges respectively. However, the optimization of the texture design is still challenging due to large number

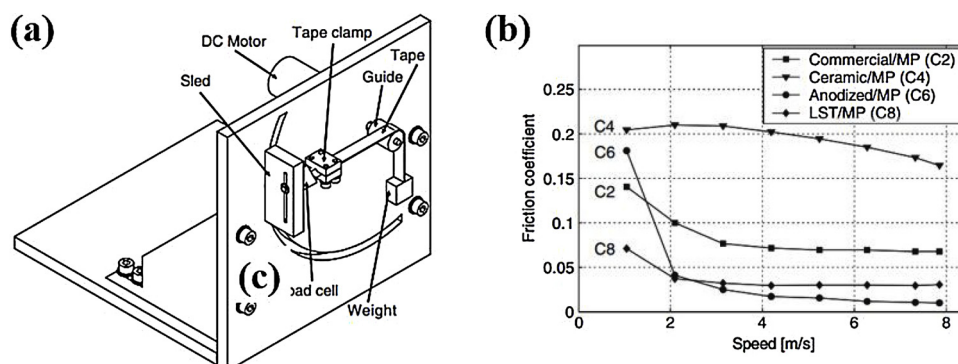


Fig. 25. (a) Experimental set up of the tape sliding over a stationary guide and (b) variation of COF with sliding speed for different surface contacts. MP stands for the metal evaporated tape, C2, C4, C6, and C8 represents the commercial guide, ceramic guide, anodized guide, and LST guide used in the experiments [158].

of variables involved and the complexity of the governing equations. Computational simulation, such as finite element (FE) method might be able to offer a more comprehensive understanding of tribological properties of engineering materials processed by LST [168]. For instance, Podgornik et al. [169] developed a 2-D finite element model (FEM) by using a Z-Set code. The SIMPLE (Semi-Implicit Method for Pressure-Linked Equations) pressure-velocity coupling algorithm was used to get the final solution. It was presented that the FEM modelling was able to capture the improved tribological performance for low texturing densities and contacts. Further improvement on the robustness and accuracy of the models and simulations will promote and extend the applicability of the LST technology.

6.2.2. LST combined with surface coatings or post-processing

To ensure the high wear resistance of the LST processed surfaces, LST combined with surface coating or post-processing techniques might be a promising solution to keep the integrity and reliability of the LST processed surfaces. Recent advances in the coating technologies such as physical vapor deposition, chemical vapor deposition, and anodizing, have enabled the development of a variety of surface coatings for improving the wear resistance of mechanical components [19,33,170,171]. The hybrid effect of LST and surface coating could help to significantly improve texture feature wear resistance. For example, Zhang et al. [172] fabricated a layer of TiAlN coating on WC/Co substrate processed by LST. It was showed that there were some combined beneficial effect of the LST and the surface coatings since the textured surface promotes the adhesion between coatings and substrate. Moreover, LST combined with post nitriding or carbonizing process have been developed in recent years and showed a great potential for improving the wear resistance [173,174]. For instance, Li et al. [174] developed a LST with surface molybdenizing duplex-treatment method on a Ni-base alloy to improve the wear resistance of the material at high temperature. The results showed that the wear rates were reduced by 4 times for the LST plus molybdenizing processed surface as compared with the surface just processed by LST. Therefore, integrating LST with other surface processing techniques, such as coating or post-processing might be further beneficial to the durability of LST processed surfaces.

7. Conclusions

This paper presents the recent advances and progress of LST and related techniques for enhancing the tribological performance of engineering materials. The process designs of LST by means of laser ablation, laser interference, and laser shock processing are discussed. The effects of laser parameters including laser type, laser power intensity, and laser pulse number on the morphology of the textured surfaces are summarized. The texture designs in terms of feature size, fraction, shape, and alignment on the tribological properties of LST processed surfaces are discussed. Furthermore, the enhanced tribological performance in terms of manipulated COF and improved wear resistance of engineering materials by LST is discussed. Applications of LST in various fields are reviewed, followed by a discussion on the current challenges and the future research direction of LST. It is envisioned that this review can offer the guideline and insights for future designs of LST processes towards enhanced tribo-performance of engineering components for a large variety of applications.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

Acknowledgements

The authors appreciate the financial support by startup funding

from the Department of Mechanical Engineering at the University of Nevada, Reno. Y. Liao appreciates the support by ORAU Ralph E. Powe Junior Faculty Enhancement Award, 2016.

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