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Laser Surface Texturing and Techniques to Improve the Tribological Properties of Materials

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Abstract - Surface texturing, a technological method in the last decade, is one of the surface modification techniques that change the surface texture to improve the tribological properties of materials. It provides an increase in the wear resistance of the materials and a decrease in the friction coefficients, as well as improving the lubrication conditions. Recently, various surface texturing processes have been developed. One of them, laser surface texturing, is the most advanced and efficient among them. Different texture density, size, depth and shape changes on the surfaces of materials with laser surface texturing have been the subject of theoretical and experimental researches. In this review study, laser ablation, laser interference and laser shock, which are the most commonly used techniques, were examined in detail from the literature and compiled within the scope of this study. In laser surface modification methods, the parameters affecting tribological properties such as texture geometry and laser power, laser pulse and laser scanning speed are discussed. The tribological behaviors of laser texturing under different operating conditions (dry and oily) were also investigated.

Keywords: Coefficient of Friction, Laser Ablation, Laser Interference, Laser Shock Processing, Laser Surface Texturing

Malzemelerin Tribolojik Özelliklerini İyileştirmeye Yönelik Lazer Yüzey Tekstür ve Teknikleri

Öz - Son on yılda teknolojik bir yöntem olan yüzey tekstür yöntemi, malzemelerin tribolojik özelliklerini geliştirmek için kullanılan yüzey modifikasyon tekniklerinden biridir. Malzemelerin aşınma direncinin artmasını ve sürtünme katsayılarının azalmasını sağlar ve bunun yanı sıra yağlama koşulları iyileştirir. Son zamanlarda çeşitli yüzey tekstüre işlemleri geliştirilmiştir. Bunlardan biri olan lazer yüzey tekstüre işlemi aralarındaki en gelişmiş ve verimli olanıdır. Lazer yüzey tekstüre ile malzemelerin yüzeylerinde farklı doku yoğunluğu, boyut ve derinlik ve şekil değişiklikleri teorik ve deneysel araştırmalara konu olmuştur. Bu derleme çalışmasında, en yaygın kullanılan teknikler olan lazer ablasyonu, lazer girişimi ve lazer şoku literatürdeki kaynaklardan detaylı olarak incelenmiş ve bu çalışma kapsamında derlenmiştir. Lazer ile yüzey modifikasyonu yöntemlerinde tribolojik özellikleri etkileyen parametrelerden tekstür geometrisi ile lazer gücü, lazer şoklama ve lazer tarama hızı gibi konular ele alınmıştır. Farklı çalışma koşulları altında (kuru ve yağlı), lazer tekstür işleminin tribolojik davranışları da ayrıca incelenmiştir.

Keywords: Sürtünme Katsayısı, Lazer Ablasyon, Lazer İnterferans, Lazer Şok İşleme, Lazer Yüzey Tekstüre

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1. Introduction

Surface modification methods have been preferred for years in order to improve tribological properties. These methods are laser surface texturing (LST) [1-4], ion beam etching/milling [5-7], lithography [8-11], hot embossing [12-14], micro-milling [15-18], electrochemical machining [19-20], and mechanical texturing [21].

Extending the lifetime of engineering materials can be provided with LST, a technology that optimizes micro topography [22]. LST is preferred among surface texturing methods due to its high efficiency, excellent controllability, environmental friendliness and accuracy [23]. In severe sliding conditions on the material, laser texturing is known to increase load bearing capacity and reduce friction [22]. Various laser methods are used in the literature to create textures on the surface of engineering materials. Direct laser ablation [23], direct laser interference [24] and laser shock processing [25] are the main methods used in LST. Comparison of LST techniques were given in Table 1.

Table 1. Comparison of LST techniques [27].

Criteria	Laser interference	Laser ablation	Laser shock processing
Efficiency	xxxx	xxxx	xxx
Flexibility	xxxxx	xxx	xxx
Surface modification effect mechanism	Heat induced phase transformation	Heat induced phase transformation	Surface plastic deformation for all metallic materials
Resolution	0.1 µm for silicon substrate	1 µm for titanium	10 µm for aluminum alloy
Applicable materials	Metals, polymer, ceramics and composite materials	Metals, polymer, ceramics and composite materials	Metals

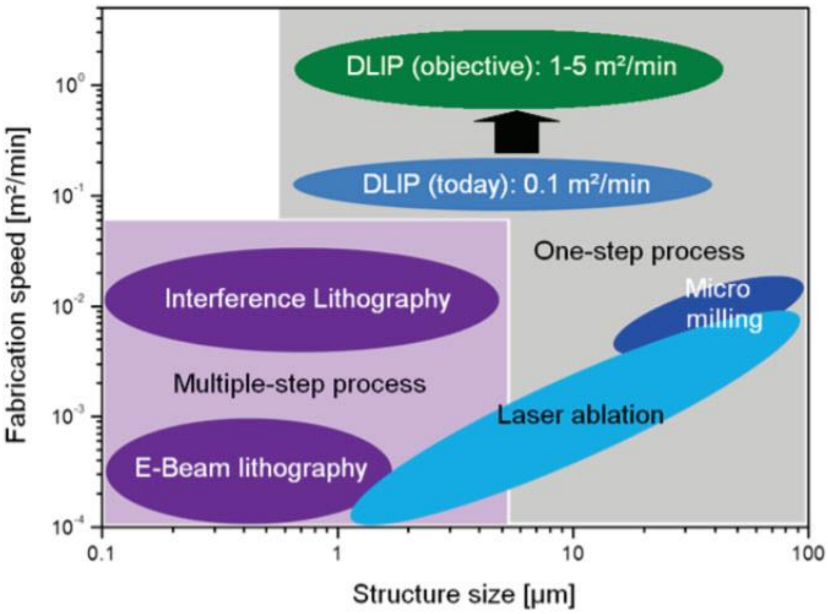

Figure 1. A comparison of different surface texturing techniques in terms of structure size and fabrication speed [26]

As can be seen in the Figure 1, the production speed can be 0.1 m^2/min with a structure size ranging from 1 to 100 µm with the laser interference technique. With this feature, it is more efficient than lithography and laser ablation techniques. Compared to the laser ablation method, the interference technique is more advantageous in terms of resolution [26].

The LST process is used to improve lubrication and increase wear behavior. With the LST technique, the decrease in the contact area between the surfaces of the materials and the increase in the surface hardness during the process increase the wear resistance of the materials [27]. In addition, the particles that worn off from the surfaces in contact trapped by the textures opened with LST, preventing the acceleration of wear [28]. The friction coefficient decreases with the decrease of the actual contact area of the surfaces in contact and the formation of the surface hardening mechanism with LST technique [29].

Micro dimples produced with LST can serve as a micro reservoir for lubricant in starved lubrication conditions and as a micro hydrodynamic bearing in full or mixed lubrication conditions [28].

Analysis of tribological parameters of engineering materials processed with LST is important for overall improvement of the process and emerging commercial applications. LST is used in biomedical applications [23] to improve the biocompatibility of ceramic implant prostheses [29] and in the automotive industry [30] to improve paint adhesion on surfaces. Tribological applications such as mechanical seals, piston rings, thrust bearings and cylinder liner segments [31] have been developed for the latest status of LST and the potential of this technology [32]. LST is used to improve surface tribology parameters on polymer surfaces such as polypropylene copolymer [30] and Polytetrafluoroethylene (PTFE) [33], ceramics [34], Ti-6Al-4V alloy (TC4) substrate surface [35].

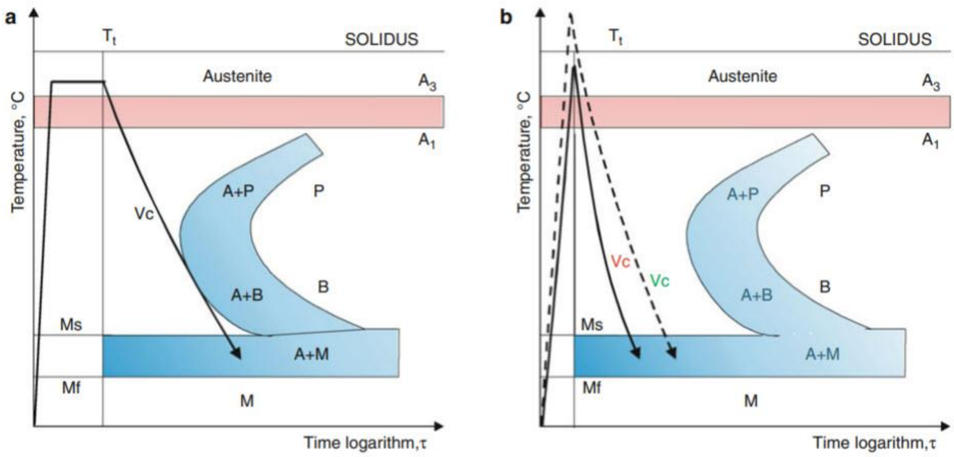

Figure 2. Schematic of hardening using (a) conventional treatment, (b) laser treatment; heat treatment [36]

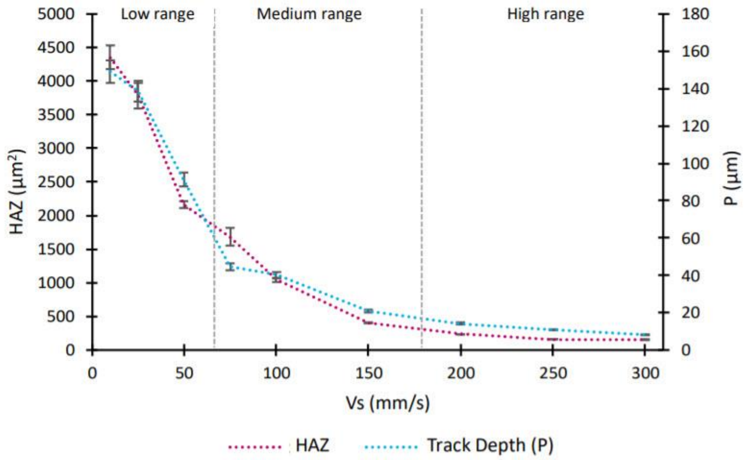

Figure 3. Heat-affected zone (HAZ) and depth of laser tracks as a function of Vs [37]

In terms of laser surface treatment, thermal effects on the material differ from other method. Figure 2 shows the schematic Time- Temperature-Transform (TTT) diagram of conventional and laser heat treatments. As it can be seen from the curves on the figure, since the laser process will be faster than the conventional process, rapid heating and cooling occurs in the microstructure. Especially in heat treatments with laser, the cooling rate is high because the area affected by the laser is quite small. Therefore, the microstructure formed after heat treatment is finer than conventional heat treatment. The thermal effect of the laser process, especially on the material, is also related to the speed of the process. In a study [37], the width of the heat affected zone (HAZ) is given in Figure 3, depending on the scanning speed of the laser process. It is seen that the HAZ decreases with the increase of scanning speed.

In this study, the effects of the worldwide existing technology related to LST on tribological applications are examined in detail from the literature and their analyzes are given. Process designs of major methods of LST techniques are reviewed and compared.

2. Laser Surface Texture Techniques (Process Design)

Studies show that there are various methods for creating textures or patterns produced on engineering materials. Among the LST techniques, commonly used three methods are: LST by Direct Laser Ablation, LST by Direct Laser interference Patterning (DLIP), and LST by Laser Shock Processing (LSP). This chapter provides a detailed review of laser surface patterning using these methods.

2.1. LST By Direct Laser Ablation

In the laser ablation process, the laser beam is directed to the working material surface and causes material loss from the surface due to heating. This situation occurs when the work material melts and evaporates from the irradiated area [38]. Material removal in the laser ablation process is due to the production of nanoparticles upon heating and melting the targeted material with the irradiated laser pulse [37]. Micro geometries realized with ultra-short pulse laser ablation technique provide advantages in terms of high accuracy, repeatability and heat [39].

Dawit Zenebe Segu et al. showed that using a pulsed Nd YAG laser, textures using circles and ellipses together on the surface of AISI 52100 steel were produced by laser ablation process (Figure 4). It has been observed that the friction coefficient of the textured surface is lower and more stable than the untextured surface. The 12% density textured surface was found to be most effective in reducing friction under test conditions (Figure 4). The positive effect of multi-scale dimples on the friction coefficient increases with dimple depth and sliding speed [40].

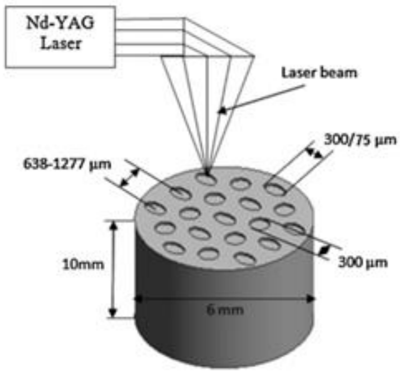

Figure 4. Schematic of laser surface texturing with laser ablation technique [40]

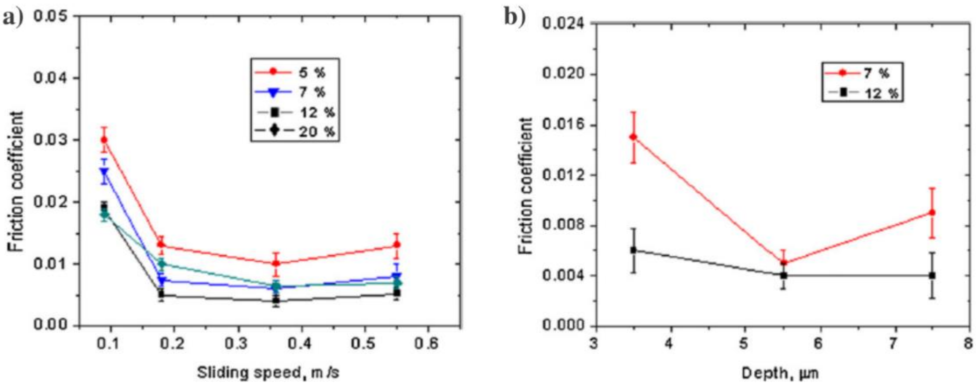

Figure 5. a) The friction coefficient of multi-scale LST with increasing sliding speed at different dimple densities b) the friction coefficient of multi-scale LST with dimple densities of 7 and 12% at different dimple depths [40]

Dawit Zenebe Segu et al. performed laser ablation by combining different shapes such as circle-square and circle-triangle on steel disc samples (Figure 6). The effect of the area density of the pits on the tribological performance was investigated under dry and coated MoS2 film [41].

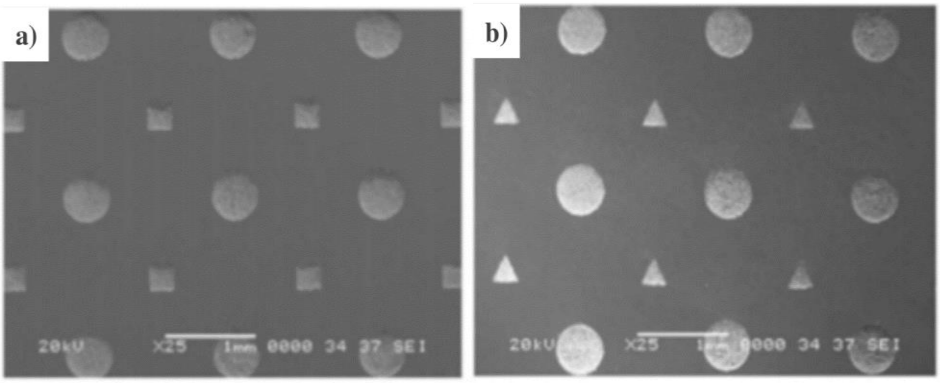

Figure 6. The surface of textured a) circle-squares b) circle-triangles [41]

2.2. Direct Laser Interference Patterning (DLIP)

With the laser beam, the surface material of the samples is melted locally and at the highest laser intensity. Periodic surface geometries, such as dot, line, and cross patterns, can be produced on a variety of materials. The spacing between the textures produced is determined by the laser wavelength, the laser target distance, and the distance between the two lasers [27]. Periodic patterns with feature sizes ranging from 5 micrometers to 15 micrometers can be created on the surface of many engineering materials [42]. Compared to laser ablation, laser interference provides higher texture resolution and the heat-affected zone is smaller. Despite the advantages that LST offers through direct laser ablation and laser interference, the heating effect in these approaches can lead to undesirable situations such as material deformation, phase transformation, thermal stresses [27].

2.3. LST by Laser Shock Processing

The target material is coated with an opaque coating to absorb the laser energy. A transparent confinement is made on the coating. During the LSP process, the laser pulse interacts with the opaque coating instead of the target material, resulting in laser-induced plasma formation. Expansion of the plasma is limited by a transparent confinement. This situation leads to the generation of a laser-induced shock wave that propagates through the target material (Figure 7). When the shock wave pressure exceeds the dynamic yield strength of the target materials, very high strain rate plastic deformation occurs on the surface of the machined specimens [27].

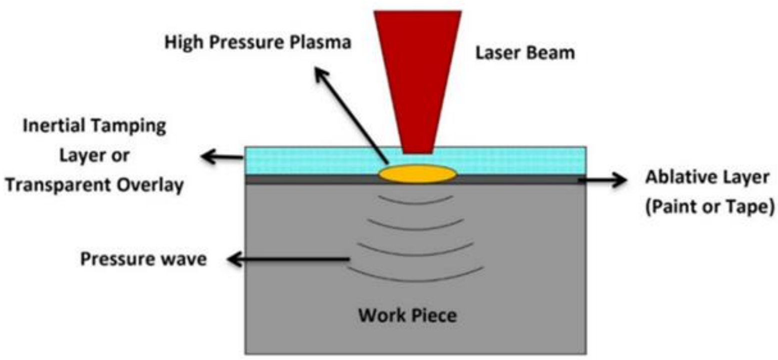

Figure 7. Schematic of laser shock processing [43]

Experiment by Wei Guo et al revealed that the samples exhibited more intensive Aluminum in layers after LSP; Therefore, it can be concluded that LSP improves the oxidation resistance of Ti6Al4V titanium alloy produced through Laser Additive Manufactured (LAM) [25].

A new processing technique called indirect laser shock surface patterning (LSSP) (Figure 8) has been found for the scalable production of texture shapes with LSP. In the indirect LSSP method, a micro mold with micro properties is placed on the surface of the material to be textured. After that, the micro mold is covered with ablative coating. This coating is applied to absorb laser energy and protect micropatterns and target sample surfaces from laser damage. A transparent confinement is placed over the ablative coating. The transparent confinement is used to limit the hydrodynamic expansion of the laser-induced plasma. This method helps the sample act as a cushion for texturing to prevent it from interacting directly with the laser energy [44].

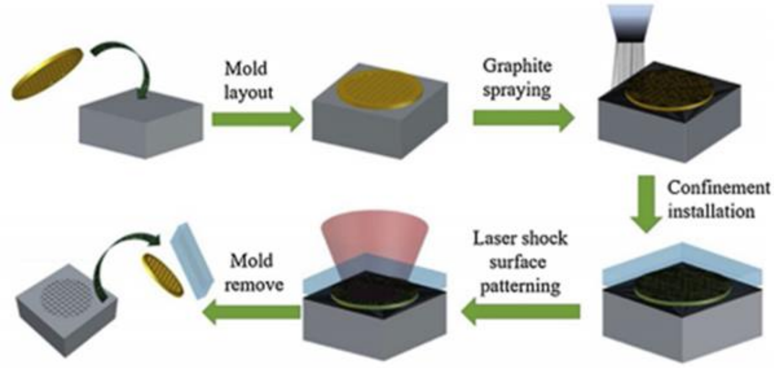

Figure 8. Schematic of indirect LSSP [44]

3. Effects of Laser Parameters on Surface Texturing

While performing the LST process, laser processing parameters such as the power density of the laser, the number of pulses and scanning speed can be controlled by adjusting. Understanding the effects of these parameters on the surface texture, determining the appropriate parametric levels, optimum design of LST processes will be helpful in improving the tribological performance of the processed materials. This section reviews the key parameters that affect the required surface texturing and the basic mechanisms related.

3.1. Laser Power Intensity

Laser power intensity (LPI) is one of the most critical LST processing parameters to determine the surface texturing effect [37]. For ablation-based and interference-based LST processes, laser power intensity affects the amount of laser energy that determines the width, depth, and shape of texture features as well as the heat-affected zone [27].

Seung Jai Won et al. applied laser surface texturing using a mesh grid mask (25 micrometer bar width) with Nd: YAG pulsed laser on an aluminum surface (Figure 9). The effects of laser intensity and laser pulse numbers were investigated by experiments. According to the experiments performed at 0.39, 3.9 and 7.8 GW/cm2 laser intensities, the surface roughness (Ra) values were found to be 1.7, 2.1 and 3.0 micrometers, respectively (Figure 10a). As a result of these, with the increase of laser intensity up to 3.9 GW/cm2, an increase in surface roughness was observed as the mass under the hole melted more and then solidified. If the laser intensity was 7.8 GW/cm2, the area where the mesh grid part contacts to the sample melted and welded to that part due to high laser intensity (Figure

10b). This situation has caused the surface of the hole region to become more irregular than the others, and thus the surface roughness has increased considerably [45].

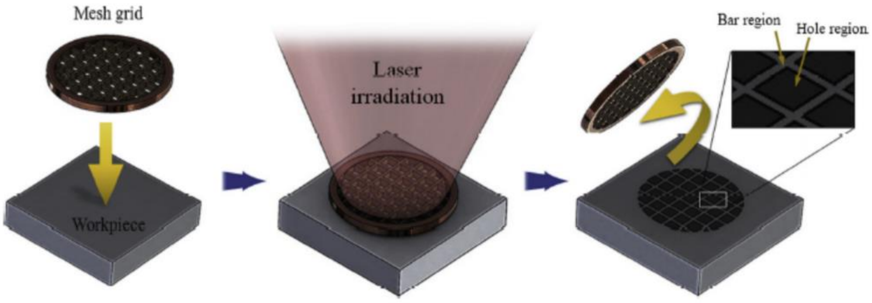

Figure 9. Schematic of experimental procedure [45]

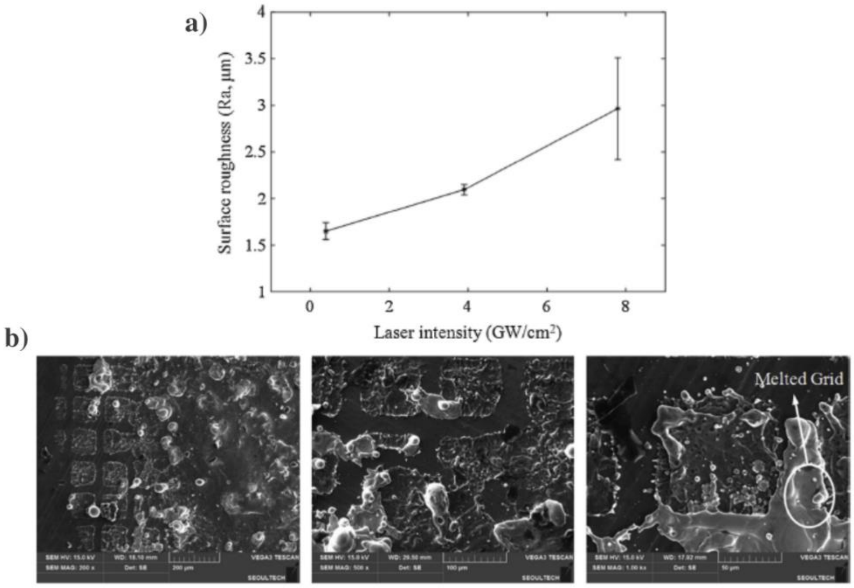

Figure 10. Surface morphologies after masked laser surface texturing with 7.8 GW/cm2 laser intensity a) surface roughness values (Ra) of the laser textured specimens at different laser intensities b) SEM images with different magnifications [45]

3.2. Number of Laser Pulses

In the LST process, the number of pulses is an important parameter for the geometry of the texture features.

Seung Jai Won et al., in their experiment, according to the results obtained under 1, 5, 10 and 20 laser pulse numbers on the aluminum, it was observed that the average depth of the bar increased at 5 and 10 pulses by 75% and 170%, respectively. On the other hand, the roughness of the hole decreased in both experiments. In the number of 20 laser pulses, a 70% increase in the width of the bars (Figure 11a) was observed, and in this case micro-scale holes were formed due to the accumulated thermal effect. Compared to the number of single laser pulses, the surface roughness values of the hole region at different laser pulse numbers decreased at 5 and 10 laser pulses by 48.7% and 77%, respectively. No change was observed in the surface roughness at 20 pulses (Figure 11b) [45].

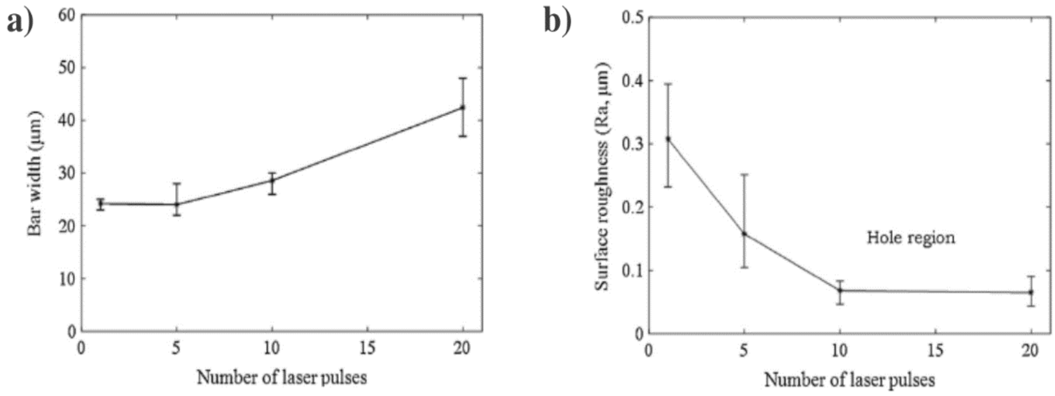

Figure 11. a) Bar width, b) surface roughness (Ra) of hole region as a function of number of laser pulses (0.39 GW/cm2 laser intensity) [45]

3.3. Laser Scanning Speed

Scanning speed is one of the important laser parameters that significantly affect the surface roughness, texture depth, surface processing efficiency and microstructure of engineering materials.

In the experiment on Ti6Al4V of Xiaoying Xi et al., the scanning speed was changed from 10mm/s to 40mm/s in the case where the average power was 14.3W and the repetition rate was 30kHz. It was observed that with the increase of scanning speed, the depth decreased (Figure 12). At 40 mm/s, the amount of melt was the maximum and the depth was the smallest. The scanning speed, in which the surface quality was better than the others, was found to be in the range of 10-20 mm/s [46].

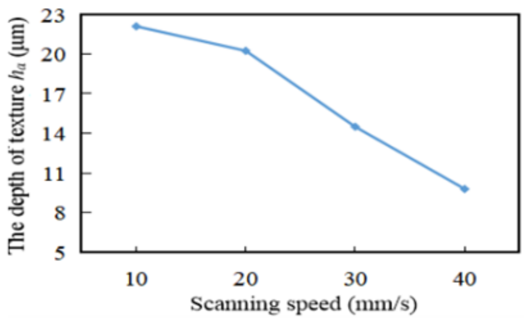

Figure 12. The relationship between h_a and scanning speed [46]

4. Enhanced Tribological Performance of Engineering Materials by LST

Tribological examination of laser parameters in the creation of textured surface textures is necessary to improve their tribological properties. The textured surface textures were studied in dry or lubricated conditions for coefficient of friction and wear resistance. It is important to understand the impact of the above parameters for the design of LST applied engineering materials and the correct selection of suitable parameters.

4.1. Texture Design

Certain types of textures are created on samples treated with LST. One of the texture types is shown in Figure 13 as an example. It is important to establish the contact between texture parameters and tribological properties for better design of the LST process. In this section, the effects of the tribological properties of texture density, size and depth, and texture shape on engineering materials are investigated.

Figure 13. LST regular micro-surface structure in the form of micro-dimples [28]

4.1.1. Texture Density

Texture density is one of the important laser parameters that affect the tribological behavior of LST processed engineering materials. The effects of texture density on wear rate and coefficient of friction were examined from the literatures.

Shuaishuai Zeng et al. performed tests on 1-Dimple and 3-Dimple samples produced on the stator surface of PTFE-based material. As a result of the test lasting 100 hours, the transfer material on the stator surface decreases as the dimples increase. It caused a reduction in the adhesion wear of the friction material due to texturing. Compared to the non-textured stator, the wear rate of the sliding friction material against the 3-dimple stator was 51.9% reduced (Figure 14) [47].

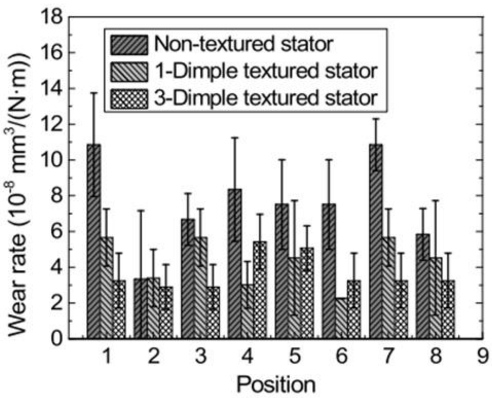

Figure 14. Wear rate of friction material [47]

According to the review by Vijay Kumar et al., the friction coefficient on the steel substrate decreased from 0.42 to 0.24 in the pin wear test (Figure 15) performed on the disc at 50% textured density [37].

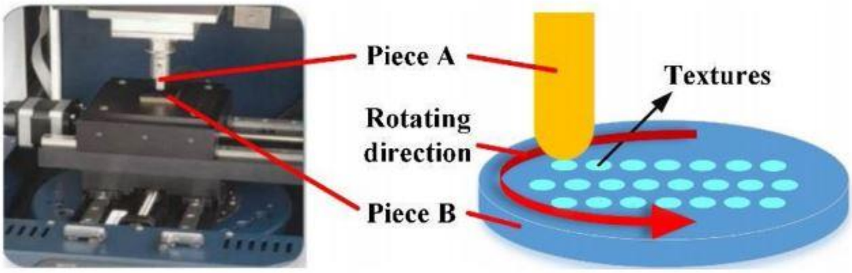

Figure 15. Schematic diagram of unidirectional rotating frictions tests [37]

Andriy Kovalchenko et al. used dimpled flat parts in their tribological experiments using oils of different viscosities (Figure 16) in a pin-on-disk friction machine. It was observed that abrasive wear increased in 5100 steel ball of discs with higher dimple density [49].

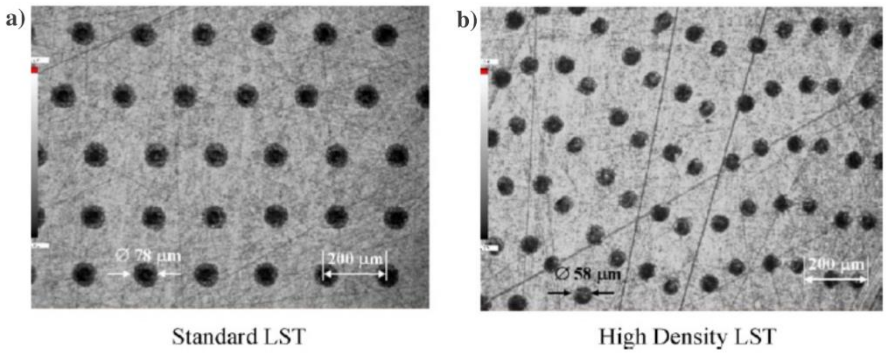

Figure 16. Optical micrographs of various disc surfaces used for testing [49]

4.1.2. Size and Depth

Another parameter affecting the tribological performance of engineering materials is texture size and depth. In this section, the effects of texture size and depth on tribological performance are examined.

Min Ji et al. produced micro tissues by laser ablation on zirconium ceramic surfaces and examined the effects of these textures on their tribological behavior. In the experiment, measurements were made on the surface at different depths and widths. The best friction performance was seen at the greatest depth that is 11 micrometers and smallest width that is 20 micrometers. (Figure 17). A small groove width is beneficial for tribological performance. With an appropriate increase in depth, tribological behavior can be greatly improved [29].

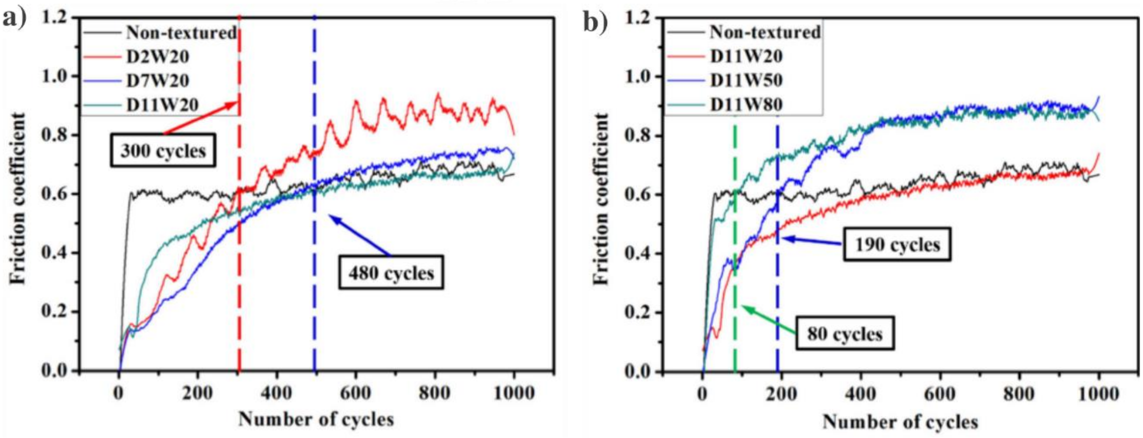

Figure 17. The curves of the friction coefficients versus different surface textures: a) different groove depths and b) different groove widths [29]

4.1.3. Texture Shape

There are various patterns in LST techniques. In this section, studies on tribological parameters about various patterns from different literatures are examined.

Demofilo ´ Maldonado-Cort´es et al. have mentioned that there are two different types of textured geometry, discrete (closed) geometries and continuous (open) geometries (Figure 18). Geometry such as circle, triangle, rectangle, and square are examples of discrete geometries. Patterns such as circle, triangle, rectangle, and square are examples of discrete geometries. Patterns such as micro-grooves, crosshatch are examples of continuous geometries. COF and wear values were examined under three different pressures on the AISI D2 steel by applying a PAO4 lubricating fluid under reciprocating test conditions. According to the experiment, the best results were observed with 38% COF reduction and 57% wear value reduction on the circle textured surface at low pressure. At high pressures, 78% COF reduction and 54% wear value reduction were observed on the S-shaped textured surface [50].

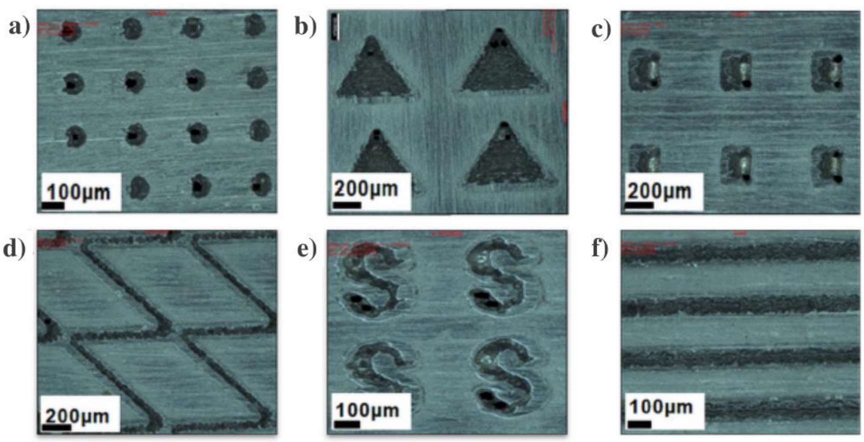

Figure 18. SEM images of LST geometries (2D), from top left to bottom right: a) circles, b) triangles, c) squares, d) crosshatch, e) "S" shape and f) lines [50]

Karthikeyan et al. performed circle, ellipse, hatch and grid pattern texturing on samples made of Ti6Al4V titanium alloy and examined the friction coefficients on the samples. Among these patterns, the maximum friction coefficient in the grid pattern and the minimum friction coefficient in the hatch pattern were observed (Figure 19) [51].

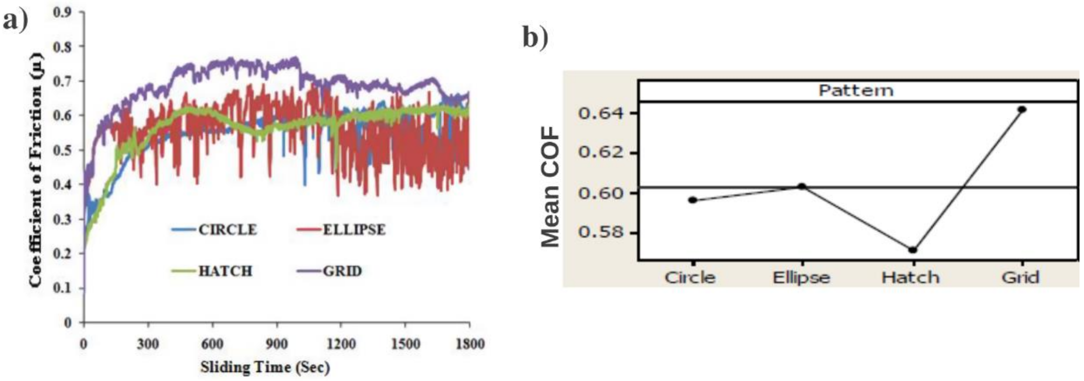

Figure 19. a) Coefficient of friction vs sliding distance for the different dimple shapes, b) the effects of pattern shape on COF [51]

4.2. Coefficient of Friction and Wear Resistance by LST

The determination of the coefficient of friction in engineering materials is important for the tribological performance of the system. The coefficient of friction and wear resistance vary in dry or lubricating conditions, in different shapes and densities. The effects of starved lubrication on the friction coefficient and wear resistance along with different parameters are discussed.

4.2.1. Dry

The effect of LST textures produced in engineering materials on COF and wear rate was investigated under dry conditions. It has been observed that laser surface texturing prevents wear debris in circular, square and triangular patterns in dry sliding conditions [52].

Tianchang Hu et al. produced micro dimple densities (13%, 23%, 44%) on the Ti-6Al-4V surface. The effects of these densities on the friction behavior in the material were investigated with dry friction and MoS_2 solid lubricant film coating. In the experiments performed under 1 N load in dry friction, it was observed that the wear increased at lower dimple density. On the other hand, it was concluded when the dimple density increased, the wear and the coefficient of friction decreased. When the load was increased to 7 N, it was observed that wear particles and wear tracks accumulated on the untextured surface and the low-density surface, and the surface exhibited a severely deformed plastic state. With 44% dimple density, the surface had a lower coefficient of friction and a longer wear life (Figure 20) [53].

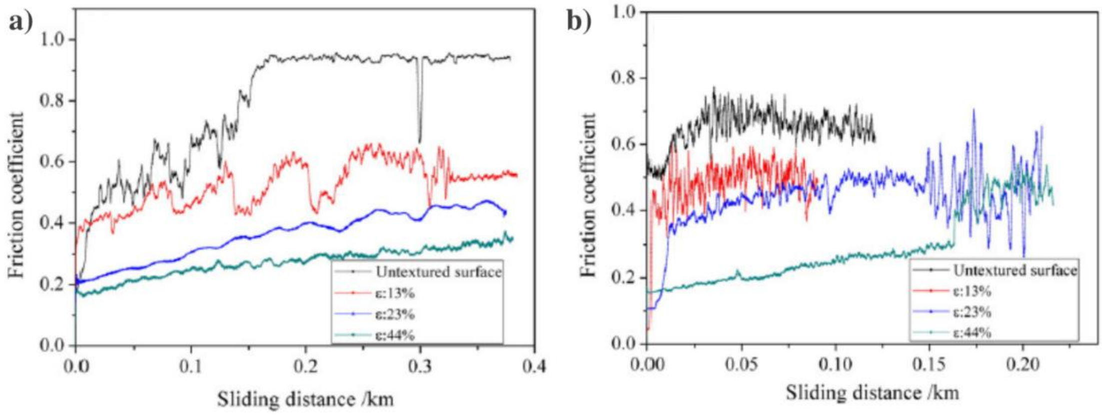

Figure 20. Friction coefficients variation as a function of sliding distance for the untextured and textured surfaces under dry friction: (a)1 N, 5 cm/s; (b) 7 N, 5 cm/s. ε indicates the dimples density [53]

4.2.2. Lubricated

The effect of LST textures produced in engineering materials on COF and wear rate was investigated under lubricated conditions. Different solid lubricants in the tested materials vary in the coefficient of friction [54].

Yixu Niu et al. produced dimples with different areal densities, diameters and depths on the surface of medium carbon steel. In case of starved lubrication on the samples, tests were carried out for friction and wear properties. For each test, 0.1 microliter of PAO4 oil was added to the contact point of the ball and disc. As a result of these experiments, the best friction coefficient and wear rate were obtained on textured surfaces with a depth of 10 micrometers, an area density of 10% and a diameter of 100 micrometers (Figure 21). In the case of starved lubrication, the amount of solid-solid contact increased and the dimple structures were abraded. This wear resulted in dry friction as no additional oil could be transferred to the contact area. After this case, the friction coefficient started to increase rapidly. The increase in the friction coefficient caused too much heat accumulation in the contact area. As a result, strong adhesive wear and oxidation of the surface were observed (Figure 22) [55].

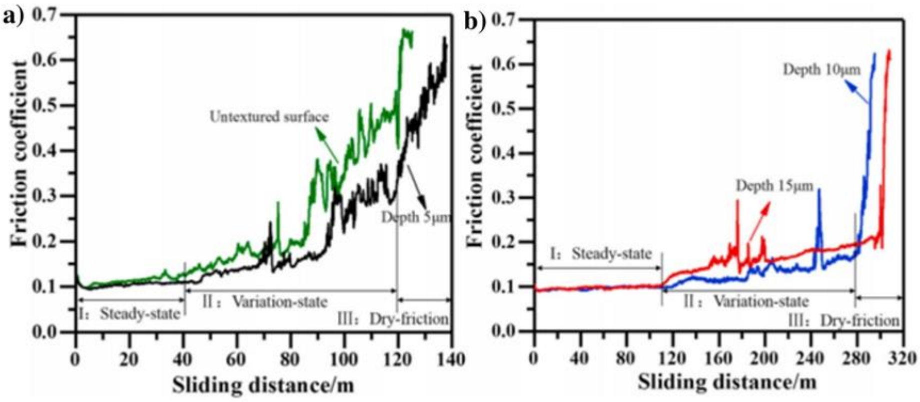

Figure 21. The friction coefficient curve of (a) untextured surface and textured surface with depth of 5 μm, and (b) depth of 10 and 15 μm [55]

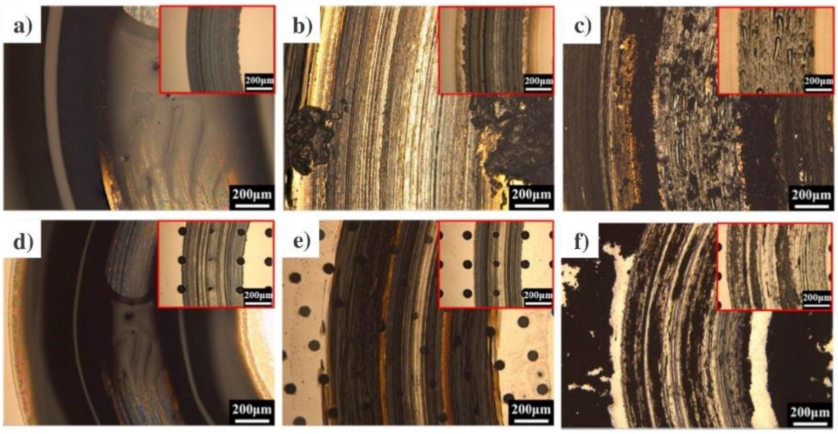

Figure 22. Optical image of the worn surface of untextured sample with sliding distance of 20 m (a), 50 m (b) and 120 m (c); and the worm surface of textured samples with depth of 5 µm where sliding distance is 30 m (d), depth of 10 µm with sliding distance of 200 m [55]

5. Conclusion

This review presents research to improve the tribological performance of surface texturing and methods on engineering materials. Different application areas and materials where LST improves tribological performance are mentioned. Direct laser ablation, direct laser interference patterning and direct laser shock process methods are discussed as LST generation techniques. The effects of laser power density, laser pulse numbers and scanning speeds on textured surfaces are mentioned as laser parameters. Textures on LST processed surfaces are discussed in terms of density, size, depth and shape. It provides the examination of COF and wear resistance, which are important parameters of tribological performance, under dry and lubricated conditions. It is envisaged that this review can provide guidance and information for the future design of LST processes to improve tribological performance of engineering components for various applications.

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