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SURFACE TEXTURING FOR TRIBOLOGICAL APPLICATIONS: A REVIEW

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Abstract: *Surface texturing is one of the surface modification techniques which deliberately change the texture of the surface, in order to improve, among other things, its tribological performance. This is obtained through different patterns, which can be on micro or nano scale, created on the contact surfaces. The performance of a textured surface depends on the shape, geometry and pattern of the surface texture and the operating condition of the components in contact. There is a number of various techniques for surface texturing, among which laser surface texturing is most often used. The different surface texture shapes, different textured area ratios and patterns, different lubrication regimes with different contact geometries and materials have been subject of theoretical and experimental research for many years. This paper reviews the state-of-the-art of researches that consider various surface texturing for tribological application, as well as its effect on performance enhancement. Conclusions of this paper may provide guidance for optimal design of surface textures in practical engineering applications.*

Keywords: *review, surface texturing, lubrication, friction, wear.*

1. INTRODUCTION

Surface texturing can be defined in several ways. In a broad sense, it can be defined as any process that artificially changes the texture of the surface. In many cases these changes are inspired by nature [1]. Defined like this, surface texturing can be obtained through some coating deposition (adding of the material) or some surface modification (without adding of the material) technique [2]. In the present review, the surface texturing will be defined as "any surface modification process that produce multiple engineered surface features of appropriate shape, geometry and pattern, which are intentionally made in order to improve the performance". It can be performed either as a micro and nano asperities (protrusions) or micro and nano holes (dimples), Fig. 1, with the latter being more popular.

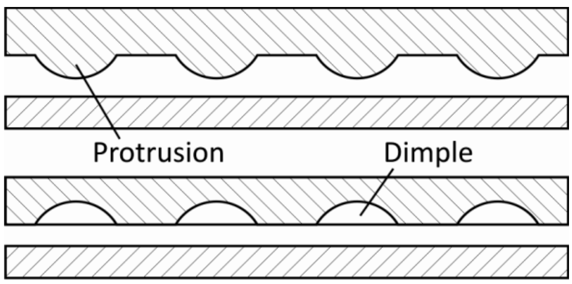

Figure 1. Different principle of intentionally made surface texturing with some surface modification technique

The earliest known commercial application of surface texturing for tribological applications is the honing of the cylinder liner [3]. Surface texturing is also known to be used in magnetic storage devices [4], as well as in MEMS devices [5] for overcoming adhesion and stiction. Surface texture in the automotive applications is mainly applied in reciprocating sliding surfaces and piston/cylinder arrangements [6,7]. This idea is also promoted in mechanical seals and sliding bearings [8-11]. Surface texturing is one of the most effective methods for tool wear reduction and improvement of tool life in the modern machining process, and thus enhancing the final product quality [12]. Biomedicine is the latest field in which surface texturing is implemented. The laser texture presents excellent results for adaptations to the biological performance of biomedical polymers. Improvement of the cellular activity on the implant surface constitutes the primary objective of the surface texture technique in biomedical applications [13].

2. SURFACE TEXTURING TECHNIQUES

The development of advanced engineering materials and precise design requirements limits the use of conventional processing methods, so the nonconventional machining processes, also known as advanced machining processes were developed. A variety of these process is being used in the industry, such as chemical, electrochemical and electro discharge machining, abrasive jet and abrasive water jet machining, ultrasonic machining, laser beam, electron beam, ion beam and plasma beam machining, each of them having their own limitations [14]. Some of these machining techniques are successfully applied in surface texturing for tribological applications. Surface modification techniques used to enhance tribological performance, through surface texturing, covers: removing material technologies, material displacement technologies, and self-forming methods, all being well described and reviewed by Coblas et al. [15].

Various techniques of surface texturing were developed over the years for enhancing tribological performance. The most promising and the most frequently used technique seems to be laser surface texturing. Its principle can be explained as a removal of material by an ablation process, i.e. by an excessive heating, melting and evaporation or sublimation of the substrate material in contact with laser beam [16]. Desired texture geometry can be obtained by utilizing the scanning optical systems so as to position the laser beam on the workpiece along a predefined trajectory. The laser surface texturing owes its effectiveness and efficiency to the laser technology utilised, due to it being rapid and permitting shorter processing times. Furthermore it is eco-friendly and due to its excellent accuracy permits strict control of the shape and size of the micro-dimples, allowing realization of optimum designs. Its ability to control energy density enables the laser to safely process hardened steels, ceramics, and polymers as well as crystalline structures [9,16].

There are also other techniques of surface texturing, and some of them are suitable for mass production, but they usually require large, expensive facilities, can show process-related draw-backs, and are not always suitable for flexible production. One of them is vibrorolling technique recommendable as a substitute for a variety of conventional, environmentally harmful techniques [17]. The vibrorolling principle is based on the transfer of hard indenter shape (pattering) on the work piece surface, by plastic deformation. Other techniques include lithography and anisotropic etching [18], photochemical etching (masking by photolithography followed by chemical etching) [19], photolithography combined with electrolytic etching process [20], focused ion beam milling [21] and abrasive jet machining [22], etc. The frequency of laser surface texturing usage compared to others techniques is presented in Table 1. It also shows the frequency of other research conditions in 40 papers, published in the last 20 years, whose research topic was surface texturing for tribological applications.

Table 1. Review of the research conditions and their representation in the surface texturing for tribological application literature

Research condition		Reference	Total number*
Surface texturing technique	Laser surface texturing	[6], [7], [8], [10], [23], [24], [25], [26], [27], [28], [29], [30], [31], [32], [33], [34], [35], [36], [37], [38], [39], [40], [41]	23
	Other techniques	[18], [19], [20], [21], [22], [42], [43], [44], [45], [46], [47]	11
Type of contact	Conformal (lower kinematic pairs)	[6], [7], [8], [10], [20], [21], [25], [26], [27], [28], [29], [33], [34], [35], [36], [38], [40], [41], [43], [44], [45], [47], [48], [49], [50], [51]	26
	Nonconformal (higher kinematic pairs)	[6], [18], [19], [22], [23], [24], [27], [30], [31], [32], [37], [39], [40], [42], [46], [52], [53]	17
Lubrication regime	Unlubricated conditions	[21], [22], [30], [31], [39], [42]	6
	Boundary and mixed lubrication	[6], [7], [10], [18], [23], [24], [26], [28], [29], [30], [32], [33], [34], [35], [36], [37], [40], [41], [43], [44], [47], [51]	22
	Full fluid-film lubrication	[8], [19], [20], [25], [27], [28], [34], [36], [38], [40], [43], [45], [46], [48], [49], [50], [52], [53]	18
Methodology of research	Theoretical researches and simulations	[8], [45], [48], [49], [50], [51] [52], [53]	8
	Experimental researches	[6], [7], [8], [10], [18], [19], [20], [21], [22], [23], [24], [25], [26], [27], [28], [29], [30], [31], [32], [33], [34], [35], [36], [37], [38], [39], [40], [41], [42], [43], [44], [45], [46], [47]	34

*Total number of references in each group of research conditions differs from 40 because in some references more than one research condition of the same group is investigated. In addition, references with simulations usually do not have the surface texturing technique defined

3. INFLUENCE OF SURFACE TEXTURING ON TRIBOLOGICAL PROPERTIES

A large number of studies have shown that the presence of artificial texturing on the surface of the kinematic pair improves their tribological properties, i.e. decrease the friction and increase the wear resistance. Among these two characteristics, the coefficient of friction is the object of interest in almost all of the studies, while the wear is investigated in only few studies. As already emphasized texturing effects are mainly beneficial, but there are studies which show the increase of coefficient of friction [6,35,43] or wear [18,54]. As an example, shot peening process leading to the creation of surface textures can cause the reduction in fatigue life of rolling/sliding concentrated contacts under mixed lubrication [55]. However, shot peening treatment followed by polishing can increase the film thickness during the start-up add reduce the asperity interactions. Further attempts have been also made to understand the effects of modified surface topography on the fatigue life of heavily loaded concentrated contacts [56].

The analysis of the Table 1 shows that the majority of surface texturing techniques use laser beam, and that most of the studies from Table 1 are experimental. The latter one can be attributed to the complexity of the phenomena and the inability of analytically describing them in many instances. However, it has been shown that the virtual texturing process and simulations [52] and theoretical mathematical models [57] can be considered as a tool for designing textured surfaces. In addition, optimization of testing conditions, such as surface texture geometrical parameters, through the design of experiments (DoE) approach [35] is also used in studies in order to reduce the necessary testing time.

The frequency of conformal (plane contact) or nonconformal (point and line contact) type of contact in reviewed papers is similar, although the conformal type of contact is more frequent (Table 1). Tribological system with nonconformal contact enable reduction of friction due to a fact that initial wear generation allows a transition of lubricated conditions from the high friction boundary lubrication to the lower friction mixed lubrication regime. The above-mentioned phenomenon is beneficial assuming that the potential of accelerated wear is acceptable in that application [11]. The regime of lubrication and the method of surface texturing highly influence the tribological behaviours of textured concentrated contacts [58,59].

A review of surface texturing on various tribological pairs has revealed that most of the studies were conducted under the boundary or mixed lubrication conditions (Table 1). The frequency of full fluid-film lubrication conditions is little bit smaller, while the unlubricated contacts were investigated in only few studies. It was shown that in full fluid-film and mixed lubrication regime, surface textures can serve as storage pockets for lubricant, generating additional micro-hydrodynamic pressure and thus reducing the contact between the surfaces. In addition, wear debris can be trapped in the artificially made dimples, reducing the effect of three-body abrasion, especially under boundary lubrication or in unlubricated conditions [11].

Influence of surface texturing on tribological properties is analysed through the influence of texture shape, texture geometry and texture pattern. It is also important to realise that this influence sometimes is not the same with conformal and nonconformal contacts or with full fluid-film lubricated, mixed or boundary lubricated or unlubricated conditions. The preview of the used texture shapes, their orientations and arrangements (arrays) and other research conditions of the selected experimental literature published in the last 20 years, whose research topic was surface texturing for tribological applications, is presented in Table 2.

3.1 Influence of surface texture shape

The mostly used texture shape is circular dimple, but hemispherical, elliptical, ellipsoidal, triangular, square and rectangular dimples, as well as different grooves are also applied and investigated. Some of them are presented in Figure 2.

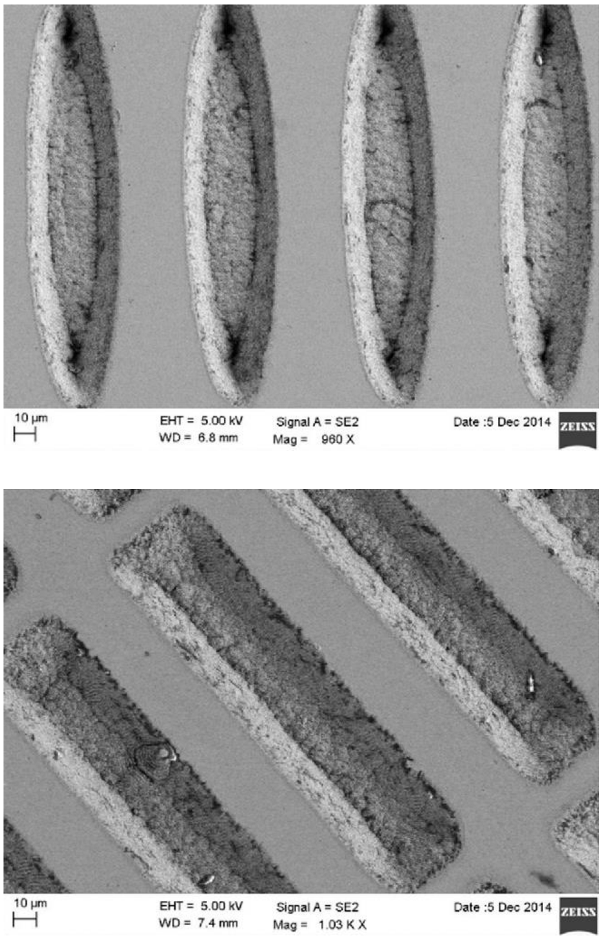

Figure 2. Representation of two different laser surface texture shapes, i.e. elliptical and rectangular dimple; high magnification SEM images [33]

The effect of the texture shapes is relatively complex to investigate, since the shapes should have similar ratio between surface dimensions and depth of the dimple/groove (aspect ratio), as well as similar area under the texture (texture density). For this reason, there are only few papers that review the effect of texture shape on tribological properties in experimental conditions. All of them are in full fluid-film or boundary/mixed lubrication conditions. Qiu and Khonsari [10] tested laser surface textured system with conformal contact and in unidirectional sliding and mainly boundary lubrication conditions.

Table 2. Preview of the selected experimental literature published in the last 20 years, whose research topic was surface texturing for tribological application (references are ordered according to the publication year)

Reference	Year	Surface texturing technique	Textured material (counter-body material)	Texture shape (orientation/array)	Contact type	Type of motion	Lubrication regime (lubricant)
Dumitru et al. [23]	2000	Laser surface texturing	Steel disc (WC-Co ball)	Circular dimples (square array)	Nonconformal (ball-on-disc)	Unidirectional sliding	Boundary and mixed lubrication (lubricating oil)
Wang et al. [25]	2001	Laser surface texturing	SiC disc (SiC ring)	Circular dimples (hexagonal array)	Conformal (ring-on-disc)	Unidirectional sliding	Full fluid-film lubrication (water)
Ryk et al. [6]	2002	Laser surface texturing	Chrome coated steel block (cast iron plate)	Hemispherical dimples	Conformal (block-on-plate)	Reciprocating sliding	Boundary and mixed lubrication (engine oil)
			Nitrided steel piston ring (cast iron cylinder)		Nonconformal (ring-on-cylinder)		
Pettersson and Jacobson [18]	2004	Lithography combined with anisotropic etching	WC/C coated textured silicon plate (bearing steel ball)	Square dimples (longi-tudinal and 30° inclined)	Nonconformal (ball-on-plate)	Reciprocating sliding	Boundary and mixed lubrication (base oil)
				Grooves (longi-tudinal and transversal)			
Costa and Hutchings [19]	2007	Lithography combined with chemical etching	Steel plate (aluminium cylinder)	Circular dimples (square array)	Nonconformal (cylinder-on-plate)	Reciprocating sliding	Full fluid-film lubrication (base oil)
				Grooves (longitudinal, inclined and transversal)			
				Chevron dimples (longi-tudinal and transversal)			
Marchetto et al. [21]	2008	Focused ion beam milling	Silicon plate (flat silicon AFM probe)	Grooves (transversal)	Conformal (pin-on-plate)	Unidirectional sliding	Unlubricated conditions
Yuan et al. [20]	2011	Lithography combined with electrolytic etching	Cast iron plate (cast iron plate)	Grooves (longitudinal, 30°, 45° and 60° inclined and transversal)	Conformal (plate-on-plate)	Reciprocating sliding	Full fluid-film lubrication (engine oil)
Qiu and Khonsari [10]	2011	Laser surface texturing	Hardened stainless steel ring (hardened stainless steel ring)	Circular dimples (square array)	Conformal (plate-on-plate)	Unidirectional sliding	Boundary and mixed lubrication (lubricating oil)
				Elliptical dimples (longi-tudinal and transversal)			

Table 2. *Continued*

Reference	Year	Surface texturing technique	Textured material (counter-body material)	Texture shape (orientation/array)	Contact type	Type of motion	Lubrication regime (lubricant)
Hu and Hu [26]	2012	Laser surface texturing	Aluminium alloy disc (steel cylindrical pin)	Circular dimples (hexagonal array)	Conformal (pin-on-disc)	Unidirectional sliding	Boundary and mixed lubrication (lubricating oil)
Segu et al. [27]	2013	Laser surface texturing	Steel cylindrical pin (steel disc)	Circular and elliptical (transversal) dimples combination	Conformal (pin-on-disc)	Unidirectional sliding	Full fluid-film lubrication (lubricating oil)
			Steel disc (steel ball)		Nonconformal (ball-on-disc)		
Braun et al. [28]	2014	Laser surface texturing	Steel cylindrical pin (steel disc)	Circular dimples (hexagonal array)	Conformal (pin-on-disc)	Unidirectional sliding	Boundary and mixed lubrication (base oil)
							Full fluid-film lubrication (base oil)
Li et al. [29]	2014	Laser surface texturing	Copper disc (steel cylindrical pin)	Hemispherical dimples (square array)	Conformal (pin-on-disc)	Unidirectional sliding	Boundary and mixed lubrication (lubricating oil)
Wang et al. [30]	2015	Laser surface texturing	Steel plate (steel ball)	Grooves (longitudinal and transversal)	Nonconformal (ball-on-plate)	Reciprocating sliding	Unlubricated conditions
							Boundary and mixed lubrication (lubricating oil)
Mohd Iqbal et al. [31]	2015	Laser surface texturing	Steel disc (steel ball)	Circular dimples (hexagonal array)	Nonconformal (ball-on-disc)	Unidirectional sliding	Unlubricated conditions
Lu et al. [32]	2016	Laser surface texturing	Steel plate (bearing steel roller)	Square dimples (square array)	Nonconformal (cylinder-on-plate)	Reciprocating sliding	Boundary and mixed lubrication (base oil)
Ancona et al. [33]	2017	Laser surface texturing	Steel truncated ball pin (aluminium alloy disc)	Rectangular dimples	Conformal (pin-on-disc)	Unidirectional sliding	Boundary and mixed lubrication (lubricating oil)
				Elliptical dimples			
Schneider at al. [34]	2017	Laser surface texturing	Steel disc (steel cylindrical pin)	Hemispherical dimples (square, hexagonal and random array)	Conformal (pin-on-disc)	Unidirectional sliding	Boundary and mixed lubrication (lubricating oil)
							Full fluid-film lubrication (lubricating oil)
Lenart et al. [22]	2018	Abrasive jet machining	Steel disc (steel ball)	Circular dimples (square array)	Nonconformal (ball-on-disc)	Reciprocating sliding	Unlubricated conditions
			Steel disc (WC ball)				

They investigated the influence of circular and elliptical (longitudinally and transversally oriented) dimples on the coefficient of friction under variable loads and speeds. All dimpled surfaces had texture density of 40 %, and dimples aspect ratio around 0.1. The results show that the longitudinally oriented (same as the sliding direction) elliptical dimples provide a significantly lower coefficient of friction compared to the circular dimple, especially under higher load.

Somehow similar conclusions were obtained by Yu et al. [45]. They investigated the influence of circular, square and elliptical dimples on the coefficient of friction of the system with conformal contact, in reciprocating sliding and full fluid-film lubrication conditions. The texturing method was photoelectrolytic etching, i.e. masking by photolithography followed by electrolytic etching. Mean contact pressure was from 0.5 to 1.0 MPa, and a maximum sliding speed was within a stroke of 0.21 – 2.1 m/s. Lubricant was commercial engine oil. All textures had two variants of texture density, i.e. 2.6 and 10.4 %. It was found that the elliptical dimples provide the lowest coefficient of friction, but in this case the orientation of the elliptical dimples was transversal, i.e. opposite to the sliding direction. The difference of the coefficient of friction values between square dimples and circular dimples is not obvious and it can also be seen that as the test load increases, the differences between all three dimple shapes become smaller. In addition, the influence between texture shapes is noticed only in the variant of texture density of 10.4 %. Samples with texture density of 2.6 %, regardless of the shape of the texture, showed similar coefficient of friction values.

In the study by Costa and Hutchings [19], it was also showed that the shape of the texture has very small influence on the maximum film thickness values in the full fluid-film lubrication conditions. They investigated three different shapes with different orientation, i.e. grooves (longitudinally, inclined and transversally oriented) and circular and chevron (longitudinally and transversally oriented) dimples. The texturing method was photochemical etching, i.e. masking by photolithography followed by chemical etching. Reciprocating sliding tests were carried out in nonconformal (cylinder-on-plate) contact and full fluid-film lubrication conditions. Lubricant was base lubricating oil (without additives), and Hertz contact pressure was from 9 to 24 MPa.

3.2 Influence of surface texture geometry

Texture geometry influence is mainly analysed through the dimensions and texture density, i.e. through two dimensionless parameters:

- aspect ratio $\varepsilon = h_p/2r_p$, where h_p is dimple depth and r_p is dimple radius,
- texture density $S_p = S_t/S$, where S_t is the total textured area and S is the total surface area

There are a large number of studies that investigate the influence of surface texture geometry on tribological properties, so only the experimental studies were reviewed. The majority of them are in full fluid-film or boundary/mixed lubrication conditions. Only two of them were in unlubricated contact conditions, which was insufficient to make some general conclusions.

As far as aspect ratio is concerned, there is agreement in the literature that an optimum can be found around 0.1 [6,10,34], even though there are examples in which aspect ratio influence is dependent on operation conditions. As example, Yuan et al. [20] investigated the influence of grooves depth on the coefficient of friction of the system with conformal contact, in reciprocating sliding and full fluid-film lubrication conditions. The texturing method was lithography combined with electrolytic etching. Three different contact pressures were used, i.e. 0.12, 0.25 and 0.5 MPa, and a maximum sliding speed was within a stroke of 0.21 – 2.1 m/s. Lubricant was commercial engine oil. All specimens were textured with grooves of the same width of 100 mm, and the same texture density of 10 %, but with two different depths (7 and 19 µm). It was found that under low contact pressure, the grooves with the depth of 7 µm show lower coefficient of friction values than those with the depth of 19 µm. On the other hand, under higher contact pressure the relation is opposite, i.e. the grooves with the depth of 19 µm show lower coefficient of friction values than those with the depth of 7 µm.

There are also studies which show that the aspect ratio does not have significant influence on tribological properties. In the previously described study by Yu et al. [45], it was showed that, in conformal contact and full fluid-film lubrication conditions, texture densities in the range from 2.6 to 22.9 % and aspect ratios in the range from 0.02 to 0.08, regardless the shape of the texture (elliptical, square and circular dimples), do not have noticeable influence on the coefficient of friction values. Somehow similar conclusions were obtained by Costa and Hutchings [19], also previously described. Results of their study showed that, in nonconformal contact and full fluid-film lubrication conditions, texture densities in the range from 2 to 24 % and aspect ratios in the range from 0.02 to 0.1, regardless the shape of the texture (grooves, and circular and chevron dimples) or its orientation (longitudinal, inclined and transversal orientation), had very little effect on the coefficient of friction values, as well as on the maximum film thickness values.

Another important parameter whose influence in improving tribological properties is also often analysed is the texture density. Some studies show that the tribological properties are improved as the texture density increase [10,27], while the other show that the influence is opposite [25,26], i.e. that the tribological properties are improved as the texture density decrease. Qiu and Khonsari [10] tested a system with conformal contact and mainly under boundary lubrication conditions. They investigated three texture densities (26, 41 and 58 %) of the circular dimples with an aspect ratio of approximately 0.1, and showed that the lowest coefficient of friction is obtained with texture density of 58 %. Similarly to this, Segu et al. [27] tested a system with conformal contact and mainly under full fluid-film lubrication conditions. They investigated four texture densities (5, 7, 12 and 20 %) of the circular and elliptical dimples combination with aspect ratio of approximately 0.02, and showed that the lowest coefficient of friction is obtained with a texture density of 20 %. On the other hand, Wang et al. [25] tested a system with conformal contact and under full fluid-film lubrication conditions. They investigated four texture densities (2.8, 4.9, 8.7 and 11 %) of the circular dimples with aspect ratio of approximately 0.06, and showed that the lowest coefficient of friction is obtained with a texture density of 2.8 %. Similarly to this, Hu and Hu [26] tested a system with conformal contact and mainly under mixed lubrication conditions. They investigated three texture densities (8.5, 17 and 35 %) of the circular dimples with aspect ratio of approximately 0.3, and showed that the lowest coefficient of friction is obtained with a texture density of 8.5 %.

There are also studies which show that there is always an optimal value of the texture density, regarding its influence on tribological properties. Schneider et al. [34] investigated the system with conformal contact, in unidirectional sliding and under two lubricated conditions (full fluid-film lubrication and mixed lubrication conditions). The texturing method was laser surface texturing. A normal contact pressure of 3 MPa was applied, and a sliding speed was varied from 0.04 to 2 m/s. Lubricant was commercial synthetic lubricating oil. They investigated four texture densities (5, 10, 20 and 30 %) of the hexagonally oriented hemispherical dimples with aspect ratio of 0.1, and showed that the lowest coefficient of friction is obtained with a texture density of 10 %. Similarly to this, Li et al. [29] tested system with conformal contact and under mixed and boundary lubrication conditions. They investigated three texture densities (5, 13 and 35 %) of the hemispherical dimples with aspect ratio of 0.01, and showed that the lowest coefficient of friction is obtained with a texture density of 13 %.

3.3 Influence of surface texture pattern

Texture pattern used in the reviewed papers differ in orientation and in arrangement (array). Orientation is consider in relation to the sliding direction, so we have: longitudinal orientation (same as the sliding direction), transversal orientation (opposite to the sliding direction), and inclined orientation (inclined to the sliding direction). Arrangement is generally: square, hexagonal or random array (Fig. 3). Similarly to the previous two influences, only experimental studies were reviewed.

Pettersson and Jacobson [18] investigated the influence of grooves and square dimples orientation on the coefficient of friction and wear of the system with nonconformal contact, in reciprocating sliding and under mixed lubrication conditions. The texturing method was lithography combined with anisotropic etching. A normal load of 5 N was applied, resulting to a Hertzian pressure of around 680 MPa. Lubricant was base lubricating oil (without additives). The samples that were compared were textured with grooves and square dimples of the same width of 20 µm, depth of 5 µm, and a texture density of 25 %. Grooves were tested in two sliding orientations, i.e. longitudinal and transversal orientation, as well as square dimples, i.e. longitudinal and 30° inclined orientation. It was found that grooves with transversal orientation show better friction and wear behaviour than the grooves with longitudinal orientation, i.e. low and stable coefficient of friction of around 0.05 is achieved, while there was no noticeable wear on textured surface or on the counter-body. Similar behaviour was noticed for the square dimples, i.e. when the square dimples pattern was inclined by 30° from the sliding direction, the coefficient of friction also became very stable and low (around 0.05), while the wear was negligible.

The positive influence of the transversal orientation of the grooves over the longitudinal orientation is also shown in the investigation performed by Wang et al. [30]. They investigated the influence of groove's orientation (longitudinal or transversal) on the coefficient of friction and wear of the system with nonconformal contact, in reciprocating sliding and under two lubricated conditions (unlubricated and mixed lubrication). The texturing method was laser surface texturing. A normal load of 2 N was applied, and a sliding speed was 5 mm/s. Lubricant was commercial synthetic lubricating oil. All samples were textured with grooves of the same width and depth of approximately 0.2 µm. The texture density was approximately 40 %. In both testing conditions (unlubricated and mixed lubrication), it was found that grooves with transversal orientation give lower coefficient of friction values than the grooves with longitudinal orientation. In unlubricated contact conditions, the average coefficient of friction values were 0.34, 0.33 and 0.29 for untextured, longitudinal grooves and transversal grooves, respectively. The average value for the transversal grooves represents a reduction of 14.9 % compared to the untextured surface. In addition, in unlubricated contact conditions, wear of this sample was lower than the wear of other two samples. In mixed lubrication conditions, average coefficient of friction values were 0.13, 0.09 and 0.08 for untextured, longitudinal grooves and transversal grooves, respectively. The average value for the textured surface presents a reduction of 33 % (for longitudinal grooves) or 38 % (for transversal groove) compared to the untextured surface.

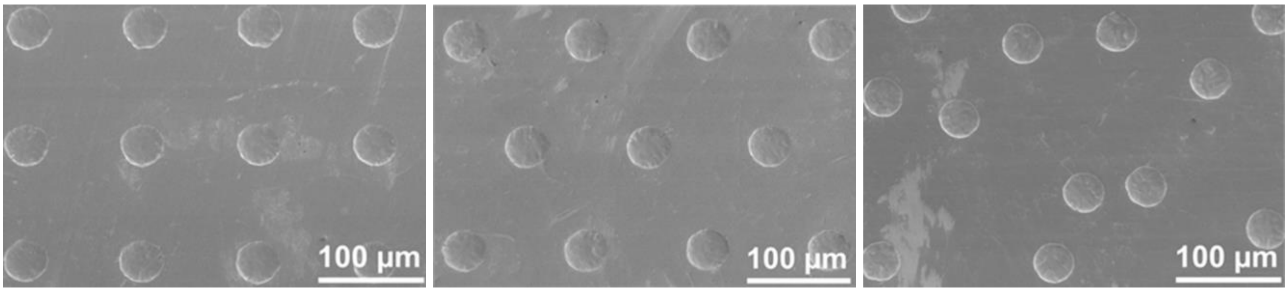

Figure 3. Representation of three different laser surface texture arrangements, i.e. square, hexagonal and random arrangement; SEM images [34]

The effect of orientation is not always so unambiguous and there are cases in which longitudinal grooves are better than transversal grooves, or in which the orientation has no effect on tribological characteristics. Results of the previously described study of Yuan et al. [20] showed that, in conformal contact and full fluid-film lubrication conditions, the transversally oriented grooves provided lower coefficient of friction values than the inclined or longitudinally oriented grooves only at lower loads and for grooves with lower depth of 7 µm. On the other hand, under higher contact pressure, longitudinally oriented grooves with the higher depth of 19 µm, provided lower coefficient of friction values than the inclined or transversally oriented grooves. Similarly to this, results of the previously described study of Qiu and Khonsari [10] showed that, in conformal contact and boundary lubrication conditions, the longitudinally oriented elliptical dimples provided a lower coefficient of friction than the transversally oriented.

On the other hand, Costa and Hutchings [19] showed that, in nonconformal contact and full fluid-film lubrication conditions, orientation (longitudinal, inclined or transversal) of the grooves and chevron dimples did not have noticeable influence on the maximum film thickness values. Nakano et al. [43] also showed that there is no influence of the grooves orientation on the coefficient of friction values. They investigated the influence of grooves of longitudinal and transversal orientation in a system with conformal contact, in reciprocating sliding under two lubricated conditions (full fluid-film lubrication and mixed lubrication). The texturing methods were milling and shot blasting combined with photolithography. Two different contact pressures was used, i.e. 1 and 6 MPa, and average sliding speed was within a range of 0.08 – 1 m/s. Lubricant was commercial lubricating oil. Two types of grooves were textured. The first group was grooves of 500 µm width, 45 – 50 µm depth and texture density of 50 %, and the second group was grooves of 60 µm width, 6 – 10 µm depth and texture density of approximately 67 %.

Similarly to the orientation influence, the different arrangements can also have some influence on tribological properties or that influence can be rather negligible. As an example, Schneider et al. [34], in the previously described study, investigated the influence of hemispherical dimples arrangement (square, hexagonal and random) on the coefficient of friction of the system with conformal contact, in unidirectional sliding and under two lubricated conditions (full fluid-film lubrication and mixed lubrication). The dimples aspect ratio was 0.1 and texture density was 10 %. It was shown that, among the dimple arrangements tested, the hexagonal one resulted in the largest reduction in coefficient of friction values compared to the untextured surface. The other two arrangements (square and random) show similar coefficient of friction values. On the other hand, Nakano et al. [43], in the previously described study, showed that there is no difference between square and hexagonal arrangements of the circular dimples. Dimples had diameter of 60 µm, depth of 6 – 10 µm and texture density of approximately 35 %.

4. CONCLUSIONS

Surface texturing is widely used in recent years in the process of improving the tribological properties of materials. This paper reviews the state-of-the-art of researches that consider various surface texturing for tribological applications, as well as its effect on performance enhancement. The most frequently used technique of surface texturing for enhancing tribological performance is laser surface texturing, and the majority of the researches were experimental.

Influence of surface texturing on tribological properties in most cases is analysed through the influence of texture shape, texture geometry and texture pattern in various research conditions, such as type of contact (conformal and nonconformal), lubrication regime (full fluid-film lubricated, mixed or boundary lubricated or unlubricated), normal load, sliding speed, temperature, lubricant type and viscosity, etc.

It was shown that in full fluid-film and mixed lubrication regime, surface textures can serve as storage pockets for lubricant, generating additional micro-hydrodynamic pressure and thus reducing the contact between the surfaces. On the other hand, under boundary lubrication or in unlubricated conditions, wear debris can be trapped in the artificially made dimples, reducing the effect of three-body abrasion.

Surface texture shape can have a significant influence on tribological properties, but there are also situations in which texture shape does not have any influence. Similar conclusions can be made for the influence of surface texture geometry and texture pattern. Therefore, it is evident that in many cases the surface texturing benefits may be better utilised when the design of surface texturing is optimised and applied to specific contact pairs. Design of experiments (DoE) approach offer such a possibility to optimise the testing condition and to reduce the necessary testing time.

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REFERENCES

[1] L. Ivanović, A. Vencl, B. Stojanović, B. Marković: Biomimetics design for tribological applications, Tribology in Industry, Vol. 40, No. 3, pp. 448-456, 2018.

[2] M. Kandeva-Ivanova, A. Vencl, D. Karastoyanov: *Advanced Tribological Coatings for Heavy-Duty Applications: Case Studies*, Prof. Marin Drinov Publishing House of Bulgarian Academy of Sciences, Sofia, 2016.

[3] E. Willis: Surface finish in relation to cylinder liners, Wear, Vol. 109, No. 1-4, pp. 351-366, 1986.

[4] U.P. Hausmann, P. Joerges, J. Heinzl, F.E. Talke: Nano-texturing of magnetic recording sliders via laser ablation, Microsystem Technologies, Vol. 15, No. 10-11, pp. 1747-1751, 2009.

[5] K. Komvopoulos: Adhesion and friction forces in microelectromechanical systems: Mechanisms, measurement, surface modification techniques, and adhesion theory, Journal of Adhesion Science and Technology, Vol. 17, No. 4, pp. 477-517, 2003.

[6] G. Ryk, Y. Kligerman, I. Etsion: Experimental investigation of laser surface texturing for reciprocating automotive components, Tribology Transactions, Vol. 45, No. 4, pp. 444-449, 2002.

[7] G. Ryk, Y. Kligerman, I. Etsion, A. Shinkarenko: Experimental investigation of partial laser surface texturing for piston-ring friction reduction, Tribology Transactions, Vol. 48, No. 4, pp. 583-588, 2005.

[8] I. Etsion, Y. Kligerman, G. Halperin: Analytical and experimental investigation of laser-textured mechanical seal faces, Tribology Transactions, Vol. 42, No. 3, pp. 511-516, 1999.

[9] I. Etsion: State of the art in laser surface texturing, Journal of Tribology, Vol. 127, No. 1, pp. 248-253, 2005.

[10] Y. Qiu, M.M. Khonsari: Experimental investigation of tribological performance of laser textured stainless steel rings, Tribology International, Vol. 44, No. 5, pp. 635-644, 2011.

[11] T. Ibatan, M.S. Uddin, M.A.K.Chowdhury: Recent development on surface texturing in enhancing tribological performance of bearing sliders, Surface and Coatings Technology, Vol. 272, pp. 102-120, 2015.

[12] P. Šugár, J. Šugárová, M. Frnčík: Laser surface texturing of tool steel: Textured surfaces quality evaluation, Open Engineering, Vol. 6, No. 1, pp. 90-97, 2016.

[13] A. Riveiro, A.L.B. Maçon, J. del Val, R. Comesaña, J. Pou: Laser surface texturing of polymers for biomedical applications, Frontiers in Physics, Vol. 6, Paper 16, 2018.

[14] M.J. Madou: *Fundamentals of Microfabrication and Nanotechnology, Volume II*, CRC Press, Boca Raton, 2011.

[15] D.G. Coblas, A. Fatu, A. Maoui, M. Hajjam: Manufacturing textured surfaces: State of art

and recent developments, Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology, Vol. 229, No. 1, pp. 3-29, 2015.
[16] G. Dumitru: Surface texturing by laser ablation, in: Q.J. Wang, Y.-W. Chung (Eds.): *Encyclopedia of Tribology*, Springer, New York, pp. 3498-3505, 2013.
[17] V.P. Bulatov, V.A. Krasny, Y.G. Schneider: Basics of machining methods to yield wear- and fretting-resistive surfaces, having regular roughness patterns, Wear, Vol. 208, No. 1-2, pp. 132-137, 1997.
[18] U. Pettersson, S. Jacobson: Friction and wear properties of micro textured DLC coated surfaces in boundary lubricated sliding, Tribology Letters, Vol. 17, No. 3, pp. 553-559, 2004.
[19] H.L. Costa, I.M. Hutchings: Hydrodynamic lubrication of textured steel surfaces under reciprocating sliding conditions, Tribology International, Vol. 40, No. 8, pp. 1227-1238, 2007.
[20] S. Yuan, W. Huang, X. Wang: Orientation effects of micro-grooves on sliding surfaces, Tribology International, Vol. 44, No. 9, pp. 1047-1054, 2011.
[21] D. Marchetto, A. Rota, L. Calabri, G.C. Gazzadi, C. Menozzi, S. Valeri: AFM investigation of tribological properties of nano-patterned silicon surface, Wear, Vol. 265, No. 5-6, pp. 577-582, 2008.
[22] A. Lenart, P. Pawlus, S. Wos, A. Dzierwa: The effect of surface texturing on dry gross fretting, Lubricants, Vol. 6, No. 4, Paper 92, 2018.
[23] G. Dumitru, V. Romano, H.P. Weber, H. Haefke, Y. Gerbig, E. Pflüger: Laser microstructuring of steel surfaces for tribological applications, Applied Physics A, Vol. 70, No. 4, pp. 485-487, 2000.
[24] T.V. Kononenko, S.V. Garnov, S.M. Pimenov, V.I. Konov, V. Romano, B. Borsos, H.P. Weber: Laser ablation and micropatterning of thin TiN coatings, Applied Physics A, Vol. 71, No. 6, pp. 627-631, 2000.
[25] X. Wang, K. Kato, K. Adachi, K. Aizawa: The effect of laser texturing of SiC surface on the critical load for the transition of water lubrication mode from hydrodynamic to mixed, Tribology International, Vol. 34, No. 10, pp. 703-711, 2001.
[26] T. Hu, L. Hu: The study of tribological properties of laser-textured surface of 2024 aluminium alloy under boundary lubrication, Lubrication Science, Vol. 24, No. 2, pp. 84-93, 2012.
[27] D.Z. Segu, S.G. Choi, J.h. Choi, S.S. Kim: The effect of multi-scale laser textured surface on lubrication regime, Applied Surface Science, Vol. 270, pp. 58-63, 2013.
[28] D. Braun, C. Greiner, J. Schneider, P. Gumbsch: Efficiency of laser surface texturing in the reduction of friction under mixed lubrication, Tribology International, Vol. 77, pp. 142-147, 2014.
[29] K. Li, Z. Yao, Y. Hu, W. Gu: Friction and wear performance of laser peen textured surface under starved lubrication, Tribology International, Vol. 77, pp. 97-105, 2014.
[30] Z. Wang, Q. Zhao, C. Wang: Reduction of friction of metals using laser-induced periodic surface nanostructures, Micromachines, Vol. 6, No. 11, pp. 1606-1616, 2015.
[31] K.Y. Mohd Iqbal, D.Z. Segu, H. Pyung, J.H. Kim, S.S. Kim: Surface texturing for low friction mechanical components, Journal of the Korean Society of Tribologists and Lubrication Engineers, Vol. 31, No. 6, pp. 287-293, 2015.
[32] P. Lu, R.J.K. Wood, M.G. Gee, L. Wang, W. Pfleging: The friction reducing effect of square-shaped surface textures under lubricated line-contacts – An experimental study, Lubricants, Vol. 4, No. 3, Paper 26, 2016.
[33] A. Ancona, G.S. Joshi, A. Volpe, M. Scaraggi, P.M. Lugarà, G. Carbone: Non-uniform laser surface texturing of an un-tapered square pad for tribological applications, Lubricants, Vol. 5, No. 4, Paper 41, 2017.
[34] J. Schneider, D. Braun, C. Greiner: Laser textured surfaces for mixed lubrication: Influence of aspect ratio, textured area and dimple arrangement, Lubricants, Vol. 5, No. 3, Paper 32, 2017.
[35] B. Meylan, F. Saeidi, K. Wasmer: Effect of surface texturing on cast iron reciprocating against steel under cyclic loading in boundary and mixed lubrication conditions, Lubricants, Vol. 6, No. 1, Paper 2, 2018.
[36] Kovalchenko, O. Ajayi, A. Erdemir, G. Fenske, I. Etsion: The effect of laser surface texturing on transitions in lubrication regimes during unidirectional sliding contact, Tribology International, Vol. 38, No. 3, pp. 219-225, 2005.
[37] P. Andersson, J. Koskinen, S. Varjus, Y. Gerbig, H. Haefke, S. Georgiou, B. Zhmud, W. Buss: Microlubrication effect by laser-textured steel surfaces, Wear, Vol. 262, No. 3-4, pp. 369-379, 2007.
[38] L.M. Vilhena, B. Podgornik, J. Vižintin, J. Možina: Influence of texturing parameters and contact conditions on tribological behaviour of

laser textured surfaces, Meccanica, Vol. 46, No. 3, pp. 567-575, 2011.

[39] D. Bhaduri, A. Batal, S.S. Dimov, Z. Zhang, H. Dong, M. Fallqvist, R. M'Saoubi: On design and tribological behaviour of laser textured surfaces, Procedia CIRP, Vol. 60, pp. 20-25, 2017.

[40] Š. Houdková, P. Šperka, M. Repka, J. Martan, D. Moskal: Shifted laser surface texturing for bearings applications, Journal of Physics: Conference Series, Vol. 843, Paper 012076, 2017.

[41] H. Kasem, O. Stav, P. Grützmacher, C. Gachot: Effect of low depth surface texturing on friction reduction in lubricated sliding contact, Lubricants, Vol. 6, No. 3, Paper 62, 2018.

[42] E.-S. Yoon, R.A. Singh, H. Kong, B. Kim, D.-H. Kim, H.E. Jeong, K.Y. Suh: Tribological properties of bio-mimetic nano-patterned polymeric surfaces on silicon wafer, Tribology Letters, Vol. 21, No. 1, pp. 31-37, 2006.

[43] M. Nakano, A. Korenaga, A. Korenaga, K. Miyake, T. Murakami, Y. Ando, H. Usami, S. Sasaki: Applying micro-texture to cast iron surfaces to reduce the friction coefficient under lubricated conditions, Tribology Letters, Vol. 28, No. 2, pp. 131-137, 2007.

[44] M. Nakano, K. Miyake, A. Korenaga, S. Sasaki, Y. Ando: Tribological properties of patterned NiFe-covered Si surfaces, Tribology Letters, Vol. 35, No. 2, pp. 133-139, 2009.

[45] H. Yu, H. Deng, W. Huang, X. Wang: The effect of dimple shapes on friction of parallel surfaces, Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology, Vol. 225, No. 8, pp. 693-703, 2011.

[46] A. Zavos, P.G. Nikolakopoulos: Tribological characterization of smooth and artificially textured coated surfaces using block-on-ring tests, FME Transactions, Vol. 43, No. 3, pp. 191-197, 2015.

[47] M.H. Sulaiman, P. Christiansen, N. Bay: The influence of tool texture on friction and lubrication in strip reduction testing, Lubricants, Vol. 5, No. 1, Paper 3, 2017.

[48] M. Qiu, A. Delic, B. Raeymaekers: The effect of texture shape on the load-carrying capacity of gas-lubricated parallel slider bearings, Tribology Letters, Vol. 48, No. 3, pp. 315-327, 2012.

[49] H. Yu, X. Wang, F. Zhou: Geometric shape effects of surface texture on the generation of hydrodynamic pressure between conformal contacting surfaces, Tribology Letters, Vol. 37, No. 2, pp. 123-130, 2010.

[50] K. Li, D. Jing, J. Hu, X. Ding, Z. Yao: Numerical investigation of the tribological performance of micro-dimple textured surfaces under hydrodynamic lubrication, Beilstein Journal of Nanotechnology, Vol. 8, pp. 2324-2338, 2017.

[51] D. Bijani, E.L. Deladi, A. Akchurin, M.B. De Rooij, D.J. Schipper: The influence of surface texturing on the frictional behaviour of parallel sliding lubricated surfaces under conditions of mixed lubrication, Lubricants, Vol. 6, No. 4, Paper 91, 2018.

[52] N. Ren, T. Nanbu, Y. Yasuda, D. Zhu, Q. Wang: Micro textures in concentrated-conformal-contact lubrication: Effect of distribution patterns, Tribology Letters, Vol. 28, No. 3, pp. 275-285, 2007.

[53] Y. Ohue, H. Tanaka: Effect of surface texturing on lubricating condition under point contact using numerical analysis, Engineering, Vol. 5, No. 4, pp. 379-385, 2013.

[54] H. Yu, W. Huang, X. Wang: Dimple patterns design for different circumstances, Lubrication Science, Vol. 25, No. 2, pp. 67-78, 2013.

[55] M. Vrbka, I. Křupka, P. Svoboda, P. Šperka, T. Návrat, M. Hartl, J. Nohava: Effect of shot peening on rolling contact fatigue and lubricant film thickness within mixed lubricated non-conformal rolling/sliding contacts, Tribology International, Vol. 44, No. 12, pp. 1726-1735, 2011.

[56] M. Vrbka, I. Křupka, O. Šamánek, P. Svoboda, M. Vaverka, M. Hartl: Effect of surface texturing on lubrication film formation and rolling contact fatigue within mixed lubricated non-conformal contacts, Meccanica, Vol. 46, No. 3, pp. 491-498, 2011.

[57] Yu. Rozhdestvensky, E. Zadorozhnaya, S. Cherneyko: Mathematical model for calculating thrust bearing with laser texturing of bearing surface, Bulletin of the South Ural State University, Series: Mathematical Modelling, Programming & Computer Software, Vol. 8, No. 1, pp. 5-24, 2015 in Russian.

[58] I. Krupka, M. Hartl, P. Svoboda: Effects of surface topography on lubrication film formation within elastohydrodynamic and mixed lubricated non-conformal contacts, Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology, Vol. 224, No. 8, pp. 713-722, 2010.

[59] I. Krupka, P. Svoboda, M. Hartl: Effect of surface topography on mixed lubrication film formation during start up under rolling/sliding conditions, Tribology International, Vol. 43, No. 5-6, pp. 1035-1042, 2010.