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STATE OF INVESTIGATIONS OF SURFACE TEXTURING FOR TRIBOLOGICAL CHARACTERISTICS IMPROVEMENT OF THE FRICTION UNITS (A REVIEW)

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Considerable amount of papers have been published on the topic of surface texturing for tribological applications over the last decade. Investigations of surface textured surfaces in bearings, seals, reciprocating automotive components, etc. are curried out in many countries. New mathematical models describing tribological behavior of the textured surfaces under different lubricating conditions are regularly elaborating. However, in spite of large amount of the studies, the quantity of mass production of the textured industrial parts of friction units is highly limited. Rather possibly that the simple surfaces texturing is not enough for the achievement of a real positive result. Application of new materials and the additional design solutions for providing geometrical precision conformability could be the ways for wider usage of the textured surfaces. The current review covers the most significant works on the surface texturing presented in scientific periodicals in English language.

The surface texture and quality is a major factor in proper and durable operation of tribological components. In general, smoother surfaces with no structural defects can reduce run-in time and retards the rate of some surface degradation processes such as contact fatigue and delamination. Smooth surfaces are particularly effective in reducing friction under boundary lubrication regimes and can promote hydrodynamic lubrication. In dry contact, however, smooth surfaces may increase adhesive component of friction mechanism. Thus, smoother surfaces are not necessarily optimal for all tribological components and applications. In addition, fabrication of very smooth finish on component surfaces is often not cost-effective. Besides, creating surfaces with minimal roughness, incorporating special structures and features with different sizes and shapes onto the surface (surface texturing) have been shown as viable means to control friction and wear behavior of tribological components.

As early as 1966 Hamilton and co-workers [1] evaluated the effects of surface texturing in the form of micro-asperities produced by etching on lubrication and suggested that the micro-asperities act as the micro-hydrodynamic bearing. This mechanism was suggested to be well suited for conformal contacts, such as mechanical seals only [2; 3].

The hydrodynamic effect of single asperity is shown in Fig. 1. The asperity on the surface projects down into the fluid flow to create a step bearing. As the flow approaches the asperity, pressure increases; on the symmetrical side, the pressure decreases but not to the ideal anti-symmetrical value as cavitation occurs on this side. The Fig. 2 shows the creation additional hydrodynamic force due to an asymmetric hydrodynamic pressure distribution over diverging and converging parts of the dimple. The pressure decreases as the flow approaches the bottom center of the dimple. On the symmetrical side, the pressure increases. The increase of pressure in converging film region is much larger than the pressure drops in diverging film region where cavitation occurs.

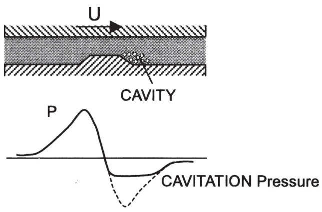


Fig. 1 The hydrodynamic effect of the idealized micro asperity

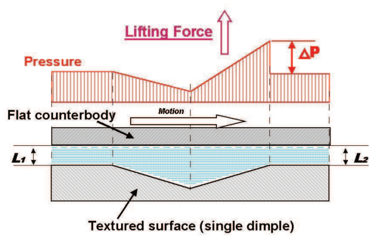


Fig. 2. The hydrodynamic effect of the single idealized dimple

Another effect acts on the condition of mixed lubrication between intimate contacting surfaces. The liquid trapped in the low region of the texture can be considered as a secondary source of lubricant, which is drawn by the relative movement to permeate into surrounding areas to reduce the friction and retard the galling. It is called the secondary lubrication effect.

Significant studies were conducted in Leningrad Institute of Precision Mechanic and Optics (former USSR) by a team led by Prof. Schneider on surface texturing by a method of vibrorolling [4–6]. Surfaces with grooves were created by plastic deformation with a rotating roller. The method allows the creation of different types of relief on flat and on round surfaces (for example, teeth of gears). The technique was shown to decrease wear and increase service life of a variety of industrial machine parts and components. About the same time, Suh and co-workers [7] presented the idea of undulated surface finish for removing oxide wear debris from the interface of electrical contacts. They initially used an etching technique which was later replaced by abrasive machining to form groves [8–11] termed undulated surfaces. The function of the undulation is to act as traps for wear debris thereby reducing the ploughing and deformation contributions to friction and wear.

Considerable amount of papers have been published on the topic of surface texturing for tribological applications over the last decade. This is largely due to the advent of cost-effective manufacturing technologies that allow fabrication of controlled and precise micro features. The texturing methods are abrasive jet machining (AJM), excimer laser beam machining (LBM), lithography, deep x-ray lithography (DXRL, also known as LIGA) and anisotropic etching. As the examples, the Fig. 3 shows an appearance of micro-dimples produced by AJM and LBM, both of which exhibited characteristic profiles. A typical example of a micro-dimpling pattern on surface is presented in Fig. 4. However, the most widely used technologies are laser surface texturing (LST) and reactive ion-beam etching (RIE). These methods are used to create micro dimples of different shapes, dimensions, depth, and distance between dimples on variety of material surfaces. LST is the most cost-effective method, but a disadvantage of LST is the creation bulges around dimples during the laser impulse impact and thermal cracks formation, especially on ceramics materials (fig. 5, *a, b*). Nevertheless, as numerous researches noted, the bulges could be easily removed by light polishing or at running-in period. RIE, AJM, LBM, lithography, LIGA technologies permit to produce dimples without material damages during texturing but these methods are more expensive.

The use of LST in tribological applications was pioneered by Etsion and his research group at Israel Institute of Technology (Technion). As it was mentioned in [12], LST is probably the most advances so far. LST produces a very large number of micro-dimples on the surface and each of these micro-dimples can serve as a micro-hydrodynamic bearing in the case of full or mixed lubrication, a micro-reservoir for lubricant in cases of starved lubrication conditions, or a micro trap for wear debris in either lubricated or dry sliding. LST permits enhance tribological characteristics as hydrodynamic [13; 14] as well as gas-dynamic seals [15–17]. These advantages confirmed experimentally [13] and substantiated by elaborated theoretical models [14–17]. It was shown in the work [18] that the maximum load-speed value of face seal can be increased by hydrodynamic effect of micro-pores. In the work [19] partial surface texturing of hydrostatic mechanical seals was investigated theoretically and experimentally. It is found that optimally textured seals generate substantially less friction and heat.

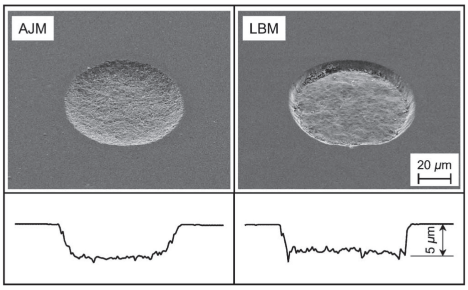


Fig. 3. Appearance of micro-dimples produced by abrasive jet machining and excimer laser beam machining, both of which exhibited characteristic profiles

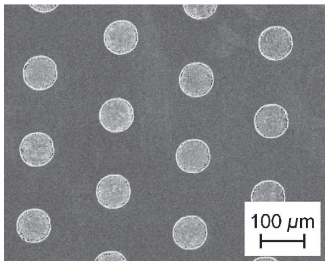
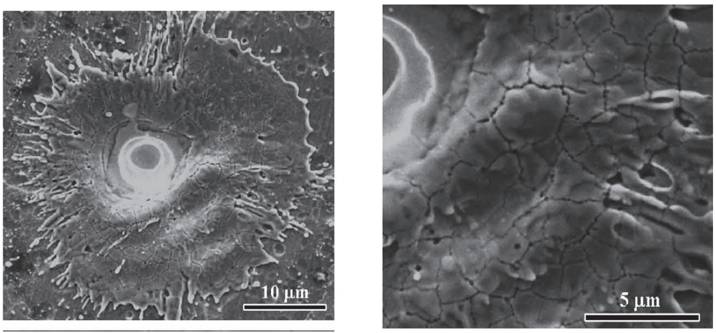


Fig. 4. An example of a micro-dimpling pattern. In this example, 80 μm dimples were distributed with a density of 15%



a *b*

Fig. 5. SEM microphotographs of a dimple produced by a single shot of Nd:VO_4 laser in ceramics (*a*) and surrounding area (*b*) with evidence of material re-melting and thermal cracking around the produced dimple

The group of prof. Kato from Japan curried out investigation of tribological characteristics of the silicon carbide textured surfaces in the conditions modeling the work the dynamic seals and thrust bearing under water lubrication conditions [20–25]. LST [20; 24] as well as ion-reactive etching [21–23] were used for surface treatment. The authors emphasized that the most evident effect of the texturing is increasing the load currying capacity due to generation an additional hydrolytic pressure. In [20–21] the effect of the parameters of texturing on the value of the coefficient of friction and the critical load for transition of lubrication mode from hydrodynamic to mixed was shown. The effect of micro-dimples on the critical seizure load was presented in [22–23]. It was shown that the texturing is an effective way to stabilize friction, to reduce friction coefficient, and to expend the low-friction range (where friction coefficient is less than 0,05) of SiC seals. It was noted that there is an optimum geometric and distribution range of micro-pits where the load carrying capacity can be increased at least twice over that of an untextured surface. The influence of running-in behavior on tribological properties is considered in [24; 25]. It was found that the maximum running load has a large influence on the load-currying capacity, which is measured as the critical load for the transition from hydrodynamic to mixed lubrication. As the result of the study, a multi-step loading running-in method is proposed to increase load-currying capacity.

In [26–28] it was substantiated the improvement of tribological characteristics of journal and thrust bearing by sliding surfaces texturing due to film thickness increasing. It its turn that was confirmed by experimental results in [27; 29–30]. It was noted in [28; 30] that the coefficient of friction can be reduced if a texture of suitable geometry is introduced. In addition, the results in [30] reveal that in the mixed lubrication regime, the so-called secondary lubrication effect in the dimpled area is the main mechanism responsible for performance improvement.

Surface texturing in reciprocating automotive components also displayed a positive effect. In [31] the Reynolds equation and the equation of motion are served simultaneously for as simplified “piston/cylinder” system with surface texturing. The solution provides the rime behavior of both the clearance and the friction force between the “piston ring” and “cylinder liner” surfaces. It is shown that optimum surface texturing may substantially reduce the friction losses in reciprocating automotive components. Further [32], an analytical model is developed to study the potential use of partial LST for reducing the friction between a piston ring and cylinder liner. The research [33] also was aimed to evaluate the effectiveness of micro-surface structure produced by LST to improve tribological properties of reciprocating automotive components. The experimental study [34] evaluates the effect of partial laser surface texturing (LST) on friction reduction in piston rings. It was found that the partial LST piston rings exhibited about 25% lower friction. Besides [35], the surface texturing increased the scuffing resistance.

The friction coefficient between a magnetic tape and a guide in a tape path can be minimized by creating micro dimples on the guide surface with laser surface texturing [36–37]. The dimples enhance the formation of an air bearing and reduce the friction coefficient between the tape and the guide due to the increased spacing.

Slider surface texturing is a promising new way to improve the tribological performance of future hard disk drives with very low flying heights [38–40]. It was found that no degradation of the read-write performance occurred and that the tribological performance of the slider was enhanced after texturing. Considering a nano-level [41], the results show that the adhesion forces and coefficients of friction of the nano-textured surface reduced noticeably compared to those of a baseline silicon oxide film surface. The nano-textures were produced by spin coating colloidal silica nanoparticle solution on a flat silicon substrate.

The test results in [42; 43] showed that laser texturing expanded the contact parameters in terms of load and speed for hydrodynamic lubrication, as indicated by friction transitions on the Stribeck curve (Fig. 6). The beneficial effects of laser surface texturing are more pronounced at higher speeds and loads, and with higher viscosity oil. The positive effect of surface texturing on friction reduction between ceramic and steel materials under lubricated sliding contact was shown in [44]. Compared to a lapped smooth surface without texturing, some samples successfully realized reductions in friction coefficient from 0.15 to 0.1. It was found that the tribological characteristics depended greatly on the size and density of the micro-dimples, whilst the dimple shape did not significantly affect the friction coefficient regardless of rounded or angular profiles. A dimple size of approximately 100 μm at a density of 5–20% is recommended. The effectiveness of the surface texturing under condition of limited lubrication and high load was shown in [45–46]. In the study [47], the micro-textured surfaces were prepared by shot blasting or milling using a shaper. The surfaces with groove patterns and mesh patterns had higher friction coefficients than the flat surfaces. The surfaces with dimpled patterns had lower friction coefficients than the flat surfaces. The results indicated that the dimpled pattern had a beneficial effect by decreasing the friction. It is found, as indicated in [48], regular microspores created by laser texturing in the fretted zone on the cylinder almost double the fretting fatigue life compared to a common non-textured fretting zone.

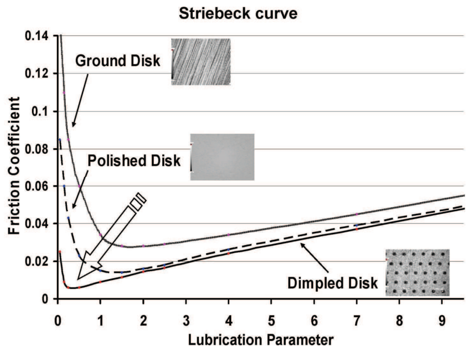


Fig. 6. The Stribeck curves of the ground, polished and dimpled (textured) surfaces [43]

The effect of surface textures on the friction of a polydimethylsiloxane (PDMS) elastomer has been investigated at both macro and microscales using a nanoindentation-scratching system [49]. Coefficient of friction on the pillar-textured surface was found to be much lower than that on the smooth surface of the same material, and it was reduced by about 59% at the macroscale tests and 38% at the microscale tests. The reduction of friction coefficient can be attributed to the reduced contact areas.

Efficiency of the laser texturing on the adhesion of the coated twist drills was shown in [50]. The results showed a large increase of the tool life when texturing of the substrate was made.

Laser treatment of tribological diamond-like coating (DLC) films was described in [51]. The results showed that the friction coefficient did not increase, as compared with the unstructured and DLC coated surfaces, and that the structure pores trapped the debris particles produced when the DLC film eventually broke. The frictional properties of the DLC film [52] are greatly improved by coating a MoS_2 layer on the nanostructured surface, while surface texturing of the nanostructured zone in a net-like patterning can increase the friction coefficient. The results demonstrate that the tribological properties of a DLC surface can be controlled using fs-laser-induced nanostructuring.

At present, the direction of study to use dimples of the textured surfaces as the reservoir for solid lubricant for providing a better working ability at dry friction is intensively developing [53–56]. It is possible to achieve a significant reduction in friction coefficient and an increase in the wear life until the scuffing inception by choosing the optimal geometrical parameters of the textured surface with the subsequent treatment.

In recent years, many new studies use the numerical method to describe parameters of the surface structure [57–60]. The new mathematical models describing tribological behavior of the textured surfaces are regularly appearing in the scientific literature [61–63]. Mathematical modeling could establish relation between structure and tribological parameters.

The bulk of studies on LST were done with conformal contact configuration. Recent studies of the effect of surface dent (dimples) on lubricant fluid film thickness with optical interferometry technique used a ball-on-flat non-conformal contact configuration were presented in [64; 65]. Results of these studies suggest that texturing could be detrimental to tribological performance in non-conformal contact configuration. It was observed that relatively deep micro-dents in the lubricated contact results in fluid film thickness reduction downstream, and can cause lubricant film breakdown. For shallower dent, this effect is reduced, or even reversed for very shallow dents. As the conclusion, results suggest that surface texturing using microdents of an appropriate depth could help to increase lubrication films capabilities.

Professor Etsion, in his interview to the journal “Tribology & Lubrication Technology” [66] expressed the confidence that surface texturing will become a common surface engineering technology, similar to the wide-spread hard coating technology. Both technologies can be used to reduce friction and wear. With coatings, that goal is achieved by adding material to a surface, while texturing achieves the same goal by removing material from the surface. Hence, in a way surface texturing can be described as an “inverse coating”. Perhaps the main difference between those two technologies is that hard coating is more beneficial under dry sliding conditions while surface texturing works better with lubricated sliding. It therefore seems reasonable to combine these two technologies to obtain low friction and wear over the entire spectrum of sliding conditions.

However, in despite of the continuously growing number of researches on surface texturing [66], as it displayed in Fig. 7, the quantity of mass production of the textured industrial parts of friction units is highly limited. It could be partly connected with an insufficient conformability of the contacting sliding surfaces of machines' parts; in the case of the defective alignment, the rough textured surface may act as abrasive to cause a damage of the mating surface. Rather possibly that the simple surfaces texturing is not enough for the achievement of real positive result in industry. Application of new materials, determination of the right choice of the materials of the contacting surfaces as well as the additional design solutions for providing geometrical precision conformability could be the ways for wider usage of the texturing surfaces.

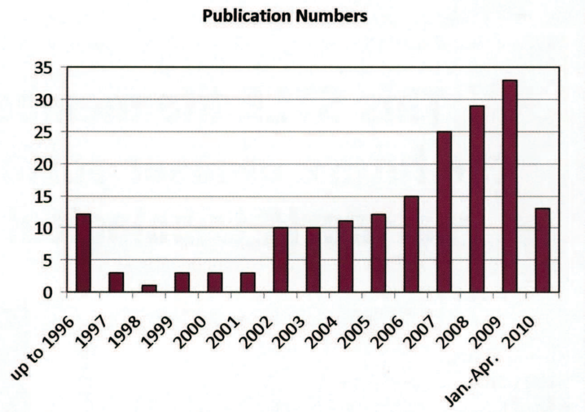


Fig. 7. The growing number of publications on surface texturing over the years before and after 1996 [66]

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Ковальченко А.М. **Стан досліджень текстурування поверхонь для покращення трибологічних характеристик вузлів тертя (Огляд)** // Проблеми тертя та зношування: наук.-техн. зб. – К.: Вид-во НАУ «НАУ-друк», 2011. – Вип. 55. – С.13–26.

В останнє десятиліття кількість досліджень трибологічних характеристик текстурованих поверхонь (спеціальної об'ємної поверхневої форми) значно збільшилась. Проводяться дослідження текстурованих поверхонь в підшипниках ковзання, торцевих ущільненях, деталях циліндропоршневої групи, деталях аудіо-записуючих пристроїв і накопичувачах електроних даних тощо; розробляються різноманітні математичні моделі, що описують режим змащування поверхонь з штучними нерівностями. Однак, незважаючи на велику кількість досліджень, використання текстурування поверхонь деталей, що виготовляються серійно, на сьогодні обмежено, оскільки для досягнення значного позитивного ефекту, є необхідним не лише безпосереднє текстурування поверхонь, але й використання нових матеріалів, і додаткових конструктивних рішень для забезпечення прецизійної геометричної сполученості. В даному огляді викладено основні сучасні роботи по текстуруванню поверхонь тертя, що опубліковані англійською мовою.

Рис. 7, список літ.: 66 найм.

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