REVIEWS

TRIBOLOGY OF MATERIALS

Tribological influences of micro texture on surface interfaces: A review

Taposh Roy[a] *, *Dipankar Choudhury*[b], *Belinda Pingguan-Murphy*[c]

Abstract

Surface texture is one of the key techniques used in surface modification in order to achieve better tribological outcomes. However, their performances are depended on the texture parameters itself, loading and lubrication conditions. The aims of this review paper are to summarise various fabrication techniques of texturing surfaces, the tribological outcomes of experimental studies on surface texturing and, scope and challenges of using a texturing surface on artificial hip or knee joints. Laser surface texturing is used in most of the surface but their application is limited mainly on flat surface. Dimpled and grooved surfaces were found to be excellent for friction reduction and fluid film thickness improvement, although the level of performance varied on both textured parameters and experiment conditions. The wear rate was found to be dissimilar among the studies. Using well-defined surface texture on artificial hip or knee joints has viable potential. However, more research should be conducted to optimize the texture parameters, and determine texture durability.

Keywords: Friction, Surface texturing, Micro-dimple, micro-groves, Wear

Abbreviations:

Significance | sample

*Correspondence: Taposh oy, Department of Mechanical and Aerospace Engineering, Monash University, Clayton, Austraila,
Tel: +61452523255
E-mail: taposh.um@gmail.com

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Background

Micro texturing such as micro-grooves or micro-dimples is one of the key techniques of surface modification (M. S. Suh, Chae, Kim, Hinoki, & Kohyama, 2010). A well designed and well-defined micro textures on a matching interface have been confirmed to be efficient in improving tribological outcomes in many successful applications, such as the surface on a golf ball (Bearman & Harvey, 1975), engine cylinders (I. Etsion, Kligerman, & Shinkarenko, 2005; Keller, Fridrici, Kapsa, Vidaller, & Huard, 2008; Ogihara, Kido, Yamada, Murata, & Kobayashi, 2000; G. Ryk & Etsion, 2006), sliding bearings and mechanical seals (I. Etsion, Halperin, Brizmer, & Kligerman, 2004; X. Wang, Kato, Adachi, & Aizawa, 2003), sliders and the disks used for hard disk drives (Ranjan, Lambeth, Tromel, Goglia, & Li, 1991), and artificial hip joints (Gao, Yang, Dymond, Fisher, & Jin, 2010; Ito et al., 2000; Sawano, Warisawa, & Ishihara, 2009). The three main mechanisms that make the textured surface unique in tribology (H.-J. Kim, Yoo, & Kim, 2012; H. J. Kim & Kim, 2009) are — (a) amplifying the hydrodynamic pressure resulting in increased load-carrying capacity and decreased wear rate; (b) storing lubricant tiny pockets to act as reserve lubricants that reduce the static and dynamic friction coefficients; and (c) trapping wear debris, thereby decreasing third body abrasive wear rate (I. Etsion, 2005; Koszela, Pawlus, & Galda, 2007; I. Křupka & Hartl, 2007; I. Křupka, Vrbka, & Hartl, 2008). Using honed or grooved surfaces began in 1910 and are widely utilized in most of modern engine cylinders, in order to reduce friction, wear, and heat generation (Dumitru et al., 2000; I_ Etsion & Burstein, 1996; Geiger, Roth, & Becker, 1998; Ito et al., 2000; Ogihara et al., 2000; Ranjan et al., 1991; C. J. Wang, Hong, & Ehmann, 1994; X. Wang, Kato, Adachi, & Aizawa, 2001; Willis, 1986). The plateau-honing technique is applied to obtain a finely polished surface, along with deep

Author Affiliation:
[a] Department of Mechanical and Aerospace Engineering, Monash University, Clayton, Austraila
[b] Department of Mechanical and Aerospace Engineering, University of Arkansas, USA
[c] Department of Biomedical Engineering, University of Malaya, Kuala Lumpur, Malaysia.

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grooves. The angle, depth, and width of cross grooves are important parameters for the plateau-honing surface. Apart from these surface parameters, the outcome of plateau-honed surfaces largely depends on the direction of the groove relative to the counterpart-sliding surface. Micro dimpling surface texturing is a relatively new technique compared with the plateau honing, and it can provide a uniform distribution of lubricant over the entire contact area without depending on the sliding direction. Aspect ratio (depth/diameter), geometry, and density are the most important parameters for achieving optimum dimple surface for a particular application (X. Wang, Adachi, Otsuka, & Kato, 2006; X. Wang et al., 2001, 2003; X. Wang, Liu, Zhou, & Zhu, 2009). Many published articles in literature are analytically based (Brunetière & Tournerie, 2012; Mezghani, Demirci, Zahouani, & El Mansori, 2012; Tala-Ighil, Fillon, & Maspeyrot, 2011; Tomanik, 2013; Torrance, 2005), whereas others are experimentally based (Antoszewski, 2012; Hu, Hu, & Ding, 2012; W. Huang, L. Jiang, C. X. Zhou, & X. L. Wang, 2012; J. Li, Xiong, Wu, Zhang, & Qin, 2012; A. Ramesh et al., 2012). This review aims to obtain answers to two basic research questions, including: (a) what are the available surface texture manufacturing processes, and their advantages and limitations. (b) How does the textured parameter influence the tribological performance?

Surface texturing Technologies

The surface texturing has been fabricated in both conventional and non-conventional manufacturing techniques since the beginning of the last century. In this section, the common practised fabricating techniques are described— the attributes, advantages, disadvantages and applications. Fig. 1 shows the general methods of fabricating surface texturing in our selected articles.

Laser Surface Texturing (LST)

Laser surface texturing (LST) is a non-contact machining process where a controlled high density of optical energy (pulsed laser), originated from laser, strikes on a targeted substrate and removes the material from the area of laser–material interaction by melting, dissociating, evaporating and expulsing. More than 40 years of the development of the laser, laser surface texturing has been performing very precise fabrication of micro dimple on almost every types of material substrate. Moreover, there are a lot of efforts for increasing the utility of LST in complex geometrical surfaces (Johan Meijer, 2004). Table 1 shows the different type of short-pulsed lasers. Among them, Nd:YAG and CO_2 are most widely used for LST applications. CO_2 lasers have wavelength of 10 μm in infrared region. It has high average beam power, better efficiency and good beam quality. On the other hand, a Nd:YAG laser consists of a beam of 1.064 microns wavelength. Usually, Nd:YAG laser have low beam power but when they operates in pulsed mode, the beam power becomes higher, thus enable to cut thicker materials. Due to shorter wavelength (1 μm), Nd:YAG can penetrate high reflective materials (glass, quartz) which are difficult to machine by CO_2 lasers (Dubey & Yadava, 2008). Mechanism of laser cutting is same in both cases the controlled scattered photons participate in penetrating into a target substrate layer by producing heat. Depending on wavelength and thermal defensibility of substrate material, the efficiency of laser on drilling can be calculated. For example, an ultra-short laser takes 1ps of thermal diffusion for the depth 10 nm drill in stainless steel. Generally, it requires 1ps, 10ps and 1ns for ultra-short laser for cutting steel, ceramic and plastic, respectively (Johan Meijer, 2004; J Meijer et al., 2002). The main advantage of ultra-short laser is— the produced heat does not have enough time to diffuse into the material depth. Consequently, it does not create a heat-affected zone and produces very fewer surface debris and recast layer in the operating zone. The adjacent layer of the textured substrate does not been affected as well. A comparison between “long” and “ultra-short” laser are shown in Fig. 2 (PAJAK, SILVA, HARRISON, & McGEOUGH, 2005).

Q. Switched Nd:YAG is widely utilised in fabricating micro dimpling surface (Andersson et al., 2007; Hu et al., 2012; Podgornik, Vilhena, Sedlaček, Rek, & Žun, 2012; Sampedro et al., 2012; Vilhena et al., 2009; Xing, Deng, Feng, & Yu, 2013; Yamakiri, Sasaki, Kurita, & Kasashima, 2011), and their mean wave length are usually 1064nm. However, to fabricate different size and pattern, the power of the peak laser needs to be adjusted. Recently, Sampedro et al. (Sampedro et al., 2012) utilised a new third generation harmonic ultra-short laser (pulse 10ps and wave length 343nm) which has very high precision capability and with negligible amount formed bulges. A shorter pulse is preferable in fabricating micro dimple because of its better efficiency in precision manufacturing but nominal chance of bulges formation and heat-affected zone [9, 11, and 12].

Electrical Discharge Machining (EDM)

Electrical Discharge Machining (EDM) is a non-contact, no-conventional manufacturing process with very high precision. It is a well-established machining process applicable to any electrically conductive material regardless of their hardness and complex geometry, which are usually very difficult to fabricate by the conventional machining process. The mechanism of EDM is simple a precisely controlled spark (tools) produces a defined thermoelectric charged energies and, these energies smash on a work piece, where dielectric fluid is used a medium (Jameson, 2001). The work piece material melts and vaporises during the high frequency spark time (Llanes, Idanez, Martínez, Casas, & Esteve, 2001). Thus, EDM mechanism is defined as a non-contact erosion process between the tool and work piece where mechanical related issues such as stress and vibration generation are not arisen (Ho & Newman, 2003; Mohd Abbas, Solomon, & Fuad Bahari, 2007). Since the first successful innovation of EDM in the late 1940s (S. Singh, Maheshwari, & Pandey, 2004), it has been

Figure 1 | **General micro fabrication surface texturing technologies.**

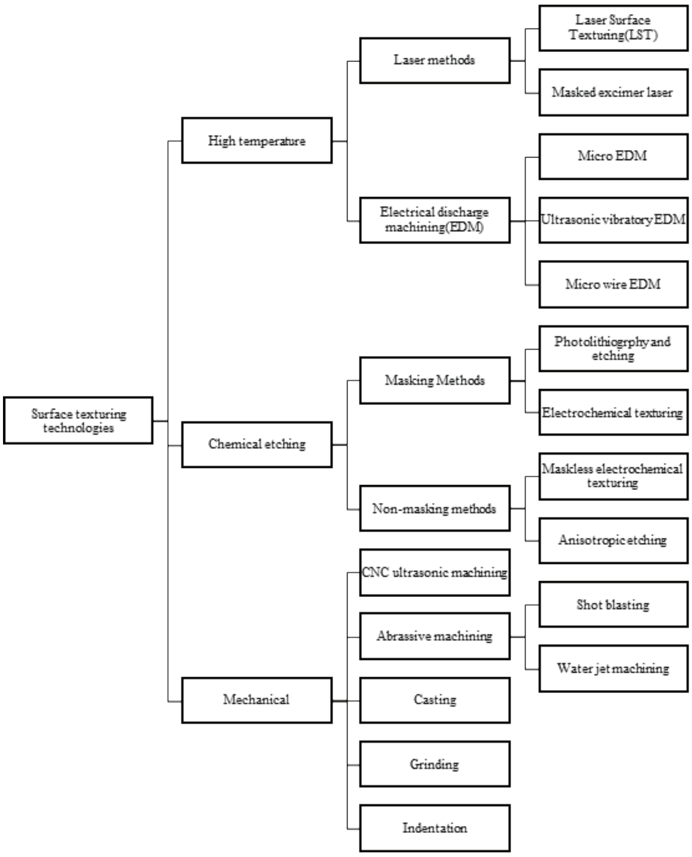


Table 1 | **Different type of short laser(Johan Meijer, 2004)**

Laser	Wavelength (nm)	Pulse length	Frequency (kHz)
CO2	10600	200 µs	5
Nd:YAG	1060, 532, 355, 266	100 ns 10 ns	50
Excimer	193–351	20 ns	0.1-1
Copper vapor	611–578	30 ns	4–20
Ti Sapphire	775	100 fs	1-250

Figure 4 | **SEM of a surface texture obtained with mask less electro chemical texturing and topography of an individual pocket obtained with mask less Electro Chemical Machining (Reconstructed from Costa, H. and I. Hutchings, 2009)**

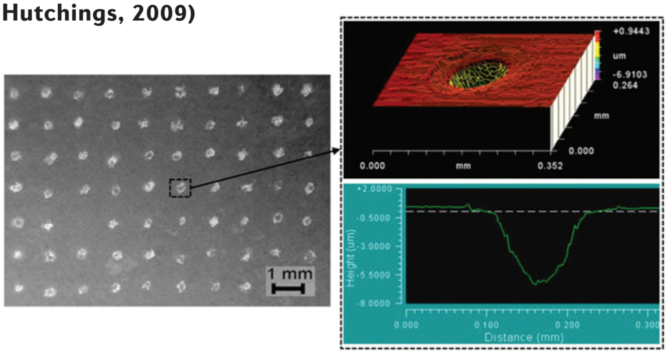


Figure 6 | **Shape and classification of shape textures: (a) discrete type and (b) continuous type (Suh, M.S., et al, 2010)**

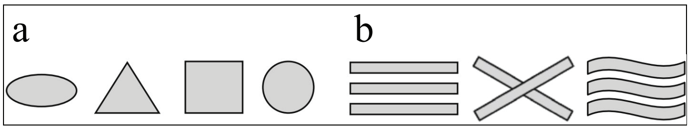


Figure 2 | **Comparison of laser machining quality, a) by long pulse laser (15ns), by ultra-short pulse laser (150fs) (Pajak, et. al, 2005)**

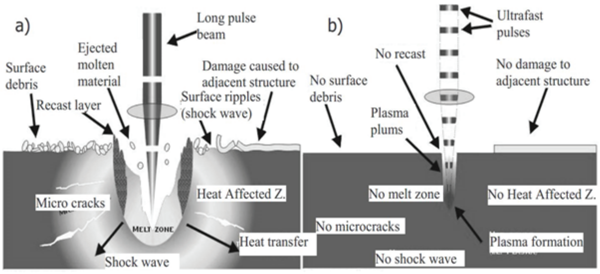


Figure 3 | **Comparison of micro-hole fabricated on tungsten carbide by, a) RC-type pulse generator (at 140V, 6.8Ω, 960.78J); b) transistor type pulse generator (at 80V, 100Ω, 21.33J) using 300μm tungsten electrodes with EDM machining process.(-Jahan, et. al, 2009)**

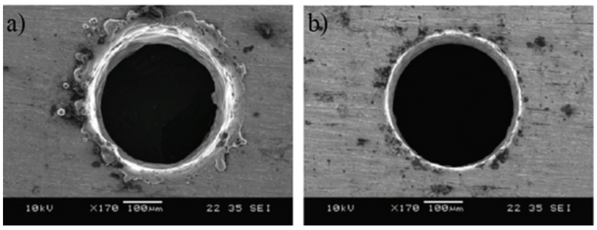


Figure 5 | **SEM image of produced dimple by abrasive jet machining and laser machining (Reconstructed from Wakuda, M., et al., 2003)**

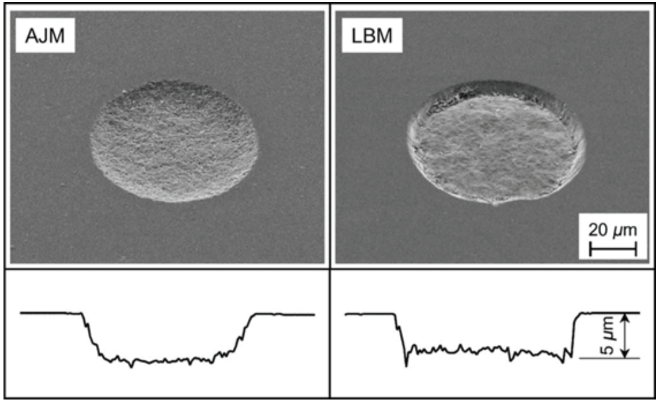
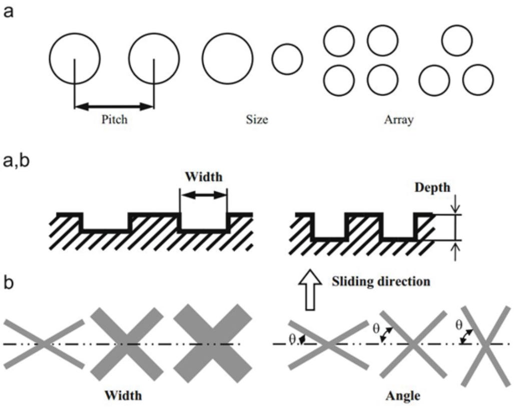


Figure 7 | **Geometry of texture parameters: (a) dimple parameters, (b) groove parameters (Suh, M.S., et al, 2010)**



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playing a great role in the micro fabrication. Furthermore, the state-of-art of EDM has become enriched after developing new advanced methods such as ultrasonic vibration EDM (Huang, Zhang, Zhou, & Zheng, 2003; Shin, Park, Kim, & Chu, 2011; Thoe, Aspinwall, & Killey, 1999; Wansheng, Zhenlong, Shichun, Guanxin, & Hongyu, 2002; Yan, Wang, Huang, & Huang, 2002; Yeo & Tan, 1999) and wire EDM (Fleischer, Masuzawa, Schmidt, & Knoll, 2004; Ho, Newman, Rahimifard, & Allen, 2004; Puri & Bhattacharyya, 2003; Rajurkar & Wang, 1993). EDM is not only capable fabricating holes and shaft as small as 3µm in diameter but also have ability producing very complex three dimensional (3D) micro cavities (Takahisa Masuzawa, 2000; T Masuzawa, Kuo, & Fujino, 1994; Rajurkar & Yu, 2000; Yu, Masuzawa, & Fujino, 1998; Zhou et al., 2011). Wire EDM was found to utilise fabricating precise microgrooves in surface texturing (Dhanik & Joshi, 2005; Katz & Tibbles, 2005) and their efficiency were depended on the current density, crater area, power dissipation and the rate of channel growth.

Electrochemical Etching

Electrochemical machining (ECM) is another non-traditional, non-contact chemical etching material removal technology governed by Faraday's laws of electrolysis (Rajurkar, Sundaram, & Malshe, 2013) (Rajurkar, Zhu, McGeough, Kozak, & De Silva, 1999). The ECM process was first introduced by Gusseff in 1929, and thereafter in 1950s and 1960s it innovated into the major newly developed engineering field such as aerospace (Huaiqian, Jiawen, & Ying, 2008; Pavlinich, Mannapov, Gimaev, & Zaitsev, 2008), biomedical (Dhobe, Doloi, & Bhattacharyya, 2011; Kamaraj, Sundaram, & Mathew, 2013), debarring (Kilickap & Huseyinoglu, 2010), and tribology (Parreira, Gallo, & Costa, 2012) for shaping, finishing and milling of a workpiece (Rajurkar et al., 2013). The advantages of this process are no tool wearing; absence of stress or burr; high metal removal rate; high surface finish; and able to fabricate very complex shape regardless of the hardness and sizes of the substrate (Bhattacharyya, Mitra, & Boro, 2002). However, ECM process depends on the electrochemical properties of a material, properties of electrolyte and supplied electrical voltage/current. Fig. 3 showed the comparison of using different supplied electrical voltage/current.

ECM process can be divided into masking and non-masking methods. Photolithography is an example of the masking method, where a chemical reagent is applied to the surface for removing material from the specific area. Thus, almost any complex irregular shape can be fabricated. For example, Shu et al.(M. S. Suh et al., 2010) fabricated a highly precise 40µm-100µm micro groves on steel by using photolithography (NaCl electrolyte with 4 V and 542 mA). Photolithography is applicable in fabricating a micro textured surface on a super hard material i.e. diamond like carbon (DLC) by using (H. Costa & Hutchings, 2009). However, Byun et al. (Byun, Shin, Kwon, Kim, & Chu, 2010) coaction r and recommended to use microsecond pulse on-time for precise manufacturing and good surface quality by using Photolithography . Again, For reducing the fabrication process time and cost, Zhu et al (Zhu et al., 2009) and Qian et al (Qian, Zhu, Qu, Li, & Yan, 2010) proposed to re-used the mask. Mask-less ECM is comparatively cheap and simple as no printing needed. The increase of electrolyte flow through the holes between workpiece and tool ensured a clean surface after the texturing operation and the formation of a uniform texture. Large separations between tool and workpiece allowed good flushing conditions (Byun et al., 2010; H. Costa, 2005). Costa (H. Costa, 2005; H. Costa & Hutchings, 2009) proposed and implemented other possible massless electrochemical machining. The method has been applied to low-carbon steel work pieces and features up to 50µm in depth hole. Highly energy consuming efficiencies, and faster process, it can be utilized as a fabrication of the texturing for applications in an industrial context. Fig. 4 shows example of a texture obtained using the optimized conditions and the profile of an individual dimple as imaged by optical interferometry.

Mechanical Machining

There are conventional and non-conventional mechanical machining processes in micro texture fabrication. Micro/nano indentation, milling, grinding, ultrasonic machining, drilling etc. are example of the conventional mechanical machining process. On the other hand, examples of non-conventional processes are shot blasting, water jet machining, abrasive water jet machining etc. Nakano et al.(Nakano et al., 2007) used both conventional (micro milling) and non-conventional (shot blasting) and revealed that in case of shot blasting, hard shot particles impact the surface at high velocity that cause damaging and roughening of the surface. The change in the surface structure is attributable to plastic deformation. It is difficult to precisely control the texture because of the large number of variables inherent in the process, such as the size, shape, velocity and hardness of the shot. In addition, shot blasting can only form random textures. Despite of these mentioned limitation, Nakano et al (Nakano et al., 2007) found a better result (precision and surface quality) from shot blasting in micro surface texturing compared to used micro milling. Moreover, the limitation of the shot blasting technique can be avoided by using a mask (mask shot blasting) the abrasive particle could be used form removing material from the selective area of the work piece. Wakuda et al (Wakuda, Yamauchi, Kanzaki, & Yasuda, 2003) used water jet machining with using mask and successfully fabricate very precise micro hole of diameter 40, 80 and 120 µm with no burr formation. Indentation is one of the most cheap and simple technique to fabricate pattern on the work piece material (I. Křupka & Hartl, 2007; Ivan Křupka & Hartl, 2008; Krupka, Svoboda, & Hartl, 2010; I. Křupka et al., 2008) but it may not be used on brittle material because of chances to create crack to the surrounding surface. Ultrasonic machining is a very economical, simple and effective method in fabricating pattern of machine components and machinery of various purposes. Ultrasonic energy of high frequency of about 22 kHz and very low and low amplitudes between 4-15 µm, is used in ultrasonic machining process. It can be also used for machining brittle ceramic material (Rajurkar, Wang, & Kuppattan, 1999; R. Singh & Khamba, 2006). Amanov et al.(A Amanov, Cho, Pyoun, Lee, & Park, 2012; Auezhan Amanov, Pyun, Zhang, Park, & Nohava, 2011) fabricate spherical micro dimple with diameter 1.25 µm using modified ultrasonic machining on steel surfaces. Another economical fabrication process can be stated as micro drilling (Cho & Park, 2011; Ma & Zhu, 2011; Roy, Choudhury, Bin Mamat, & Pinggu-an-Murphy, 2014). With the assistance of CNC programming highly precise fabrication can be achieved although there is a limitation with the size of the drill bit, and a machining on a hard material. In this case, a harder tool and little rougher substrate are expected to avoid the chance of breaking and slipping of the operating tool bit.

Effect of precise manufacturing of surface quality

Manufacturing of a well-defined surface is always a challenging while the tolerance of the dimensions is needed to be precisely maintained at the micro or nano-level. Above mentioned manufacturing techniques (section 2.1-2.4) are all well established and have own features and limitations. Along with precise manufacturing facilities, there is another key concern the possibility of changing of bulk surface properties and qualities. Materials that exhibit a high degree of brittleness, or hardness, and have favourable thermal properties (such as low thermal diffusivity and conductivity) are well suitable to LST. It is typically a mask-free technique, and it is not only a highly precision technique but also it can improve surface mechanical properties such as hardness, toughness and residual stress. AJM can fabricate micro texture in difficult-to-reach areas, generating less heat compared with conventional machining processes. Wakuda et al.(Wakuda et al., 2003) fabricated micro dimple on ceramic surface by LST and AJM, Fig. 5 shows micro dimple fabricated by LST and AJM.

ECM is ahead over other techniques since it does not affect the material either in terms of thermal or mechanical properties; however, it is a slow process. Photolithography is a form of EDM techniques which is highly effective in producing well-defined geometrical patterns on target surfaces (H. L. Costa & Hutchings, 2007; M. S. Suh et al., 2010; X. Wang et al., 2009). Various methods have been proposed for further improving in machining productivity of Photolithography, for example amplify tool electrodes could increase productivity (B. Park, Kim, & Chu, 2006; M. S. Park & Chu, 2007); Using customised pulses generator simultaneously with electrodes will enhance the capability of fabricating multiple holes with different size (M. S. Park & Chu, 2007). Adding ultrasonic vibrations with EDM can increase the penetrating capabilities in deeper hole by increasing dissolution rates(Yang, Park, & Chu, 2009). Jeon et al.(Jeon, Kim, & Chu, 2006) utilised ECM and EDM together, and got better surface quality.

CNC micro drilling is able to fabricate precise dimples in metal or ceramic surfaces(Nakano et al., 2007). It is an economical manufacturing process, and tolerances can be maintained to very high standards with CNC programming. However, the usefulness of the process depends upon the availability of the specific size and shape of the drill bit. Creating a micro pit less than 200 µm is difficult, particularly when it operates drilling into hard and abrasive materials. Furthermore Roy et al. (Roy et al., 2014) pointed out there was decease in material hardness and toughness in the edge of dimple, however they confirmed there were no foreign particle in the holes generated from drill bit after proper cleaning the dimple area. Ultrasonic machining is a unique manufacturing process Many researchers have shown by analytical and experimental studies that surface texturing can provide potential benefit in reducing friction and wear. Some of them (it means more than one, so at least two reference please) are very substantial, as the reduction in friction by 37% or more for a pin (hardened steel)-on-disk (silicon nitride ceramic) demonstrated by Wakuda et al. (I. Etsion et al., 2005) – while others have shown no effect or even a negative effect to adding surface micro-texture (REF_ at least two). Analytical studies are mostly limited to analysis of hydrodynamic effects, but show reasonably good agreement with experimental data(Choudhury, Walker, Roy, Paul, & Mootanah, 2013). Many researchers showed analytical model of hydrodynamic lubrication of texture surfaces by Reynolds equation (Ai & Cheng, 1996; de Kraker, Rixen, van Ostayen, & van Beek, 2007; Dobrica & Fillon, 2009; I_ Etsion & Burstein, 1996; Izhak Etsion, Kligerman, & Halperin, 1999; Han et al., 2011; Kligerman, Etsion, & Shinkarenko, 2005; Jiang Li & Chen, 2007; Sahlin, Glavatskih, Almqvist, & Larsson, 2004; Q. J. Wang & Zhu, 2005). Few articles have reported that the Reynolds equation is not accurate when inertial effects are important, when the Reynolds number is high, Re~ > 48, when the textures have high depth to width ratio, or when the film thickness is larger than the texture depth (de Kraker et al., 2007; Dobrica & Fillon, 2009; Han et al., 2011; Jiang Li & Chen, 2007). Few articles reported that, to find out the amount of generating hydrodynamic lift from surface textures, the Navier–Stokes equations must be solved (Arghir, Roucou, Helene, & Frene, 2003; Sahlin et al., 2004).

Continuous type

The tribological characteristics depended greatly on the size and density of the micro-grooves, and the geometrical characteristics of the surface textures have a significant effect on the tribological behavior. Crucial parameter of micro-grooves can be defined as groove width, depth, length, pitch, angle, array pattern, edge

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contour and texture area ration. Several analytical model showed the effective influences of micro-groove to increase the hydrodynamic lift which reduces the friction and wear and also increases the load carrying capacity (Adatepe, Bıyıklıoglu, & Sofuoglu, 2013; He, Chen, & Wang, 2008; Kaneta, Guo, Wang, Krupka, & Hartl, 2013; Shi & Ni, 2011). Suh et al.(Min Soo Suh & Chae, 2008; M. S. Suh et al., 2010) fabricated different groove by varying width, groove angle and array pattern. Their key findings, friction reduced achieved with crosshatched microgroove texturing and crosshatch angle of groove texture had an important influence, friction decreases according to decrease of the groove aspect ratio (groove depth over groove width). Youqiang et al.(Xing, Deng, Feng, et al., 2013; Xing, Deng, Wu, & Cheng, 2013) reported wavy-groove and linear groove surface texture with solid lubricant and dry contact. Among the patterns, the wavy-grooved samples exhibit the lowest friction coefficient and wear rate; and a large texture density showed the best results in reduction of friction and wear, followed by linear groove compared to polished surface. Wu et al. investigated the influence of area density of textures on the tribological performances by Taguchi method (Wu, Deng, Xing, Cheng, & Zhao, 2012). They fabricated groove texture surface on cemented carbide and rubbed against Ti–6Al–4V alloy and reported, the area density of textures played major contribution of both average friction coefficient and wear rate of Ti–6Al–4V alloy balls. Higher area density of textures (?? How much) is beneficial to improve tribological performance of the cemented carbide samples. Sliding speed seems to have no effect on the tribological performance of groove surface within the reliability interval of 90% (Wu et al., 2012).

Sliding direction is also an important factor in micro-grooves. Parallel and perpendicular to the sliding direction are two extreme cases of groove orientation. Researchers tried to find out the better orientation and texture parameter with different conditions. With the application of light load the friction reduced more for perpendicular sliding direction than that parallel sliding direction reported by Moronuki and Furukawa (Moronuki & Furukawa, 2003). The reason suggested was that, the grooves perpendicular to sliding could minimize the adhesion force due to water capillary, which became essential at light pressure conditions. Similar results also reported by Pettersson and Jacobson(-Pettersson & Jacobson, 2004) and Costa and Hutchings(H. L. Costa & Hutchings, 2007). Pettersson and Jacobson worked on micro-groove of two small grooves (5 and 20 μm) and found high friction and wear with parallel sliding direction because a very small circular contact area is likely to cross an oil reservoir. However, the friction and wear reduced with the perpendicular oriented grooves over the sliding direction. Costa and Hutchings conduct reciprocating sliding tests of line contact varying the magnitudes of applied loads. At normal load (write value of contact pressure) condition, perpendicularly oriented grooves over the sliding direction showed better result in friction and wear reduction. However, at low load condition, parallel oriented grooves to the sliding direction showed better result. They pointed out at higher Hertz contact pressure, the lubricant squished away from the contact through the parallel groove. Ren et al. (Ren, Nanbu, Yasuda, Zhu, & Wang, 2007) established a mixed-elastohydrodynamic model to simulate the effects of micro-groove in a slide-to-roll contact. They showed grooves perpendicular to sliding direction offer the strongest hydrodynamic lift with compare to other orientation. Zum Gahr et al. (Zum Gahr, Wahl, & Wauthier, 2009) investigated the friction coefficient and film thickness of 100Gr6/ceramic pairs to see the orientation of grooves to sliding direction, which found grooves perpendicular to the sliding direction generated greater film thickness and lower friction coefficient than that of parallel orientation. Yuan et al. (Yuan, Huang, & Wang, 2011) improved the elastohydrodynamic model and did experimental investigation. They reported three conclusions, at low relatively low contact pressure grooves perpendicular to the sliding direction performed better, at relatively high contact pressure parallel orientation performed better and the grooves with an angle between parallel and perpendicular to the sliding direction would be the best at most cases which could reduce friction up to 44%.

Discrete type

Discrete type surface texture is a relatively new technique with compare to continuous type surface texture, and many studies have been proven its potentiality, that is higher than other texture surface (Grabon, Koszela, Pawlus, & Ochwat, 2013; Nakano et al., 2007) (Table 2, 3). The discrete type surface texture in micro scale and circular shape generally called micro dimple. In general, surface texture expanded the range of parameters under which hydrodynamic lubrication took place, leading to a longer span of low friction, hydrodynamic lubrication to occur before increases in friction due to area contact (contact between two moving objective) occurred. The benefit of discrete type surface texture in reduction of friction force is almost twice due to increased influences of hydrodynamic lubrication with compare to continuous type texture surface (Grabon et al., 2013). Amanov et. al showed, circular dimpled surface texture with lowest density and smallest diameter showed the lowest friction coefficient and resistance to wear among the dimpled specimens(Auezhan Amanov, Tsuboi, Oe, & Sasaki, 2013). Lowest dimple density of 5% exhibits the lowest friction and wear and smallest dimple diameter that showed the similar result of previous study (Auezhan Amanov et al., 2013). For the first time, Segu et al. used multi scale surface texture of the combination of circular and elliptical shape dimple with a wide range of dimple density(5% to 20%) at fixed size dimple, 300 (circle diameter) and 300/150 (axial

Table 2 | **Tribological performances of discrete type texture surface. In the table D= equivalent diameter/width in μm; W= pitch in μm; A= texture area density (%); L=applied load in N; P= contact pressure in MPa; V= sliding speed in mm/sec**

Specimen	Texture shape	D	W	H	A	L (P)	V	Key results
Ceramic(Wakuda et al., 2003)	Circular	40, 80 and 120	-	5	7.5, 15 and 30	- (780)	0.012–1.2	Dimple size of approximately 100μm and area density of 5–20% showed better result with all sliding speed.
Poly dimethylsiloxane(J. Li, Zhou, & Wang, 2011)	Circular	30-500	92.5-2000	5	4.9-22.9	0.95,1.88 (0.1867,0.2344)	20-200	With area density 4.9% and at low speed range (<60 mm/s) friction coefficient reduced up to 89%.
Steel(Krupka et al., 2010)	Circular	90-120	50	0.2	-	29(505)	-	Textured surface increased film thickness up to 260% of that of no textured surface.
Steel(Ivan Křupka & Hartl, 2008)	Circular	90-120	50	0.23-1.02	-	28(505)	1.4-27	For higher dimple depth the film thickness is larger.
Steel(I. Křupka et al., 2008)	Circular	90-120	100	0.2-0.3	-	28(505)	1.3-5.4	Textured surface increased the film thickness as well improve the rolling contact fatigue (RCF) (Existence of RCF decrease the life of components).
Steel(I. Křupka & Hartl, 2007)	Circular	90-120	100	1.1-1.9	-	28(505)	22	Film thickness increased with the textured surface at high depth of dimple but it diminishes at the low depth of the dimple.
Polyoxymethylene(Cho & Park, 2011)	Circular	125	-	125	5, 10, 20, 30	- (1.35)	100	Lowest friction coefficient showed with 10% area density which reduced friction about 50%.
Poly dimethylsiloxane(W. Huang, L. Jiang, C. Zhou, & X. Wang, 2012)	Circular	50-200	70-1100	5	2.6 – 40.1	0.95(0.084)	3 - 200	High area density and small size dimples become critical for reducing friction.
Bronze alloy (Lu & Khonsari, 2007)	Circular	2000,4000		165,448	20	445-1112 (0.114 – 0.284)	0.409-409	Proper dimple size, shape and depth are essential to reduce the friction coefficient with textured surface.
Ti6Al4V(Hu et al., 2012)	Circular	150	-	40	13, 23, 44	1-10 (2.5-12)	50-400	Textured surface with area density of 23% showed the lowest coefficient of friction (0.1) but for longer wear life, area density with 44% is better.
Steel(Kovalchenko et al., 2011)	Circular	58,78	80-200	5, 5.5	12, 15	10(700)	30-760	Dimple surface with 12% area density showed the lowest friction coefficient (0.06). Wear in the dimple surface was less in low pressure but much more in high pressure.
Si_3N_4(Yamakiri et al., 2011)	Circular	11-35	60 - 120	4 - 24	3 - 23	11-80 (0.1-0.8)	42-250	Textured surface helps to reduce friction and the dimples trap the abrasive particles at the same time. Dimple diameter is required to be more than 20μm for improving result.
NiCrMo(Borghi, Gualtieri, Marchetto, Moretti, & Valeri, 2008)	Circular	100	50	-	40	1–10 (1-10)	100-1200	Textured surface for normal loads larger than 3 N, friction coefficient reduced of about 75% from no-textured to textured surface.
Steel(Andersson et al., 2007)	Circular	35,50	65-110	13-30	8,30	50-2000	40-160	Textured surface significantly reduced both friction and wear under lubricated sliding conditions.
DLC(Chouquet, Gavillet, Ducros, & Sanchette, 2010)	Circular	7,65	-	0.3, 1.3	14, 22	- (1100)	550-6850	Friction coefficient reduced significantly in case of low sliding speed values (area density 14%), reduced friction up to 83%.
Steel(Byun et al., 2010)	Circular	300	1000	5	5	150(2.98)	10-80	At low sliding speed (10mm/s) textured surface showed 75% lower friction but at high sliding speed (80 mm/s) friction was same.
Brass(X. Wang et al., 2009)	Circular	20-60	-	0.6-1.2	7	5–30 (74 - 128)	20-210	Dimple diameter of 20 μm at 210 mm/s found the best effect, decreased 15.6% at the load of 10 N with compared to no-textured specimen.
Steel(Qiu & Khonsari, 2011)	Circular, elliptical	200-2000	-	50,55	40	4.5-36 (0.00118-0.00943)	6.7-670.38	Higher area density showed the lower coefficient of friction as well increase the load carrying capacity. Elliptical dimpled specimens wear quicker than the circular dimpled specimens.
Steel(Ma & Zhu, 2011)	Elliptical	200-600	-	5-20	12.6-60	2-30	380	Optimum dimple depth increases while the optimum dimple diameter decreases as the speed becomes larger and the load becomes smaller.
Carbon steel(Auezhan Amanov et al., 2011)	Spherical	1.25, 1.7, 1.0	-	0.054-0.198	-	10(2320), 30(3350)	0.085, 0.15	Large dimple (1.7μm) reduced friction by 23% and wear loss also been reduced by14%.
Steel(A Amanov et al., 2012)	Spherical	1.25	-	0.07	-	20-100	50	Friction reduced by 25% and wear loss also been reduced by 60%.
Stainless steel(Ashwin Ramesh et al., 2013)	Square	28	44	42	31.8	125-254	**50**	**Friction reduced by 25% and wear loss also been reduced by 60%.**

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length for elliptical dimple) (Segu, Choi, & Kim, 2013). They reported, the area density of about 12% was the most effective in reduction of friction and wear.

Like large scale diverging-converging surfaces, micro-scale discrete type shape can act as an asymmetric pressure distribution that causes hydrodynamic lift. In mixed lubrication condition, this hydrodynamic lift can change the balance between hydrodynamic and boundary lubrication by reducing the contact area during operation, and thus reduces friction and wear. Several studies showed that, the amount of friction and wear reduction largely independent of texture shape, and highly dependent on size, depth, depth to diameter ratio, area density and also dependent on the contact area between two moving object. Kovalchenko et al. (Kovalchenko, Ajayi, Erdemir, & Fenske, 2011; Kovalchenko, Ajayi, Erdemir, Fenske, & Etsion, 2005) conducted a series of experiments at the lubricating regime transitions by using a pin-on-disk test rig in unidirectional sliding, with a discrete type surface textured. Six different types of surface including un-textured, textured with or without lapping in two different types of lubricant. They showed Stribeck curves for various lubricants and load conditions, and different dimpled area densities where the depth to diameter ratio was maintained same for all cases. All the micro texture dimpled samples showed the transition of lubrication regime from boundary to hydrodynamic lubrication for both high and low viscosity oil. At lowest speed fully hydrodynamic lubrication was maintained for optimal dimple case. For dimpled surfaces with higher area density, an increase in hydrodynamic regime was observed, but the hydrodynamic lift of dimple effect was lost at low speed and high loads (the sample had not been polished after producing dimple). Therefore, the study recommended that a textured surface could be effective in reducing friction through lubrication regime change. However, accelerated wear could make a textured surface tribologically detrimental, where wear is undesirable, especially in those components where high precision and stability of dimension are required. Several analytical studies have looked at more closely, considering the effects of dimple size and shape for specific applications (Siripuram & Stephens, 2004). Stephens and Sirpuram (Siripuram & Stephens, 2004) studied the effects of different cross-section shapes, where circular, square, diamond, hexagonal and triangular cross-sections were considered, over a range of area densities. They established a model based on Reynolds equation and showed that minimum friction coefficient was independent of the shape of the texture but had an influence of the area density. Krupka and their groups experimentally showed the clear evidence of micro dimple surface texture effect on lubrication film thickness (I. Křupka & Hartl, 2007, 2009; Krupka et al., 2010; I. Křupka et al., 2008). They studied on the effect of size and shape of micro-features, as well as of slide-to-roll ratio on lubricant film thickness. They showed the evidence of increasing 260% and 100% in lubrication film thickness compared with a polished surface during start-up and dynamic conditions, respectively. Well-defined micro-dents could alter the thin film thickness in highly loaded non-conformal contact surfaces by varying dent depths. The results within a lubricated zone indicated that the thin film thickness decreased for a set of deep micro-dents, whereas film thickness was thicker for the lighter deep dents. The scenario was not the same in the slide-to-roll conditions; thickness was influenced less in the latter cases. Etsion, with others, has published several experimental studies and established theoretical model to find out the optimal dimple parameters with evenly spaced dimple created with laser machining fabrication process (Brizmer, Kligerman, & Etsion, 2003; Izhak Etsion, 2004, 2005; Izhak Etsion et al., 1999; G Ryk, Kligerman, & Etsion, 2002). The dimples were arranged in rectangular patterns. An early model developed for mechanical seals indicated that evenly distributed, hemispherical dimples could substantially increase the load-carrying capacity of mechanical seals(Izhak Etsion et al., 1999), in cases where hydrodynamic lubrication was more important than hydrostatic (relatively low pressure drop across the seal). Qiu et al. (Qiu & Khonsari, 2011) used two types of dimple shape with three arrangements, 1) circular, 2) elliptically shaped radially oriented, and 3) elliptically shaped circumferentially oriented dimple on stainless steel with uni-directional test rig. A circumferentially oriented elliptical dimple array with a density of 40% performed best; the entire specimen showed lowest friction coefficient which increased the load-carrying capacity. Lu et al. (Lu & Khonsari, 2007) studied similar patterns of dimpled surfaces (circular, elliptical, and non-textured) on journal bearings and suggested that an elliptical shape could reduce the friction coefficient most effectively among their experimental surfaces. However, the performances elliptical shaped dimple is influenced by the direction of sliding.

Discussion

The surface texture in the field of tribology has been a subject of intense research, since last several years. Many Universities, research organizations, and industries got actively engaged in this research area, started from last decades. The in-depth study of the mechanisms behind surface texture was initiated in different fields to clarify the insitu durability of interacting material surfaces. There has been a multidisciplinary approach of the systems, making it an attractive area of research, involving researchers from different fields.

As shown in Fig. 8, the friction coefficient of untextured specimen ranges from 0.14 to 0.12. The friction coefficient of textured surfaces depends on the area density of dimple patterns. In both cases, the friction coefficient decreases firstly with the increase of the area density, but then increases sharply. While the pattern is textured on the steel side as shown in Fig. 8, the friction coefficient can be reduced when the area density ranges from 5% to 20%. But

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if the area density exceeds 20%, an effect of friction increase will be presented. In this group of experiments, the dimple pattern with an area density of 10% has a lower friction coefficient than other patterns at all rotational speeds. Compared with untextured specimen, the dimple pattern with an area density of 10% shows an obvious decrease in friction coefficient. The maximum decreasing value is 53% at the condition of 200 rpm (Zhang, Huang, Wang, & Wang, 2013).

The effect of micro texturing on sliding surface interaction is very complex, depending on the lubrication regime, loading and other external conditions, surface materials, and other factors. Several analytical and experimental studies have shown that surface texturing can provide benefits – some very substantial, as the reduction in friction by 30% or more for a piston-ring-like case demonstrated by Etsion – while others have shown no effect or even a negative effect to adding surface micro-texture. In applications where a substantial amount of mixed lubrication takes place, friction and wear can most likely be reduced with the application of micro-dimpling, where the exact geometry of the pores is determined by the specifics of the application. In boundary and dry sliding cases, the potential for friction reduction or lifetime extension via micro texturing is highly dependent on the surfaces and loads involved. Attention must be paid to the type of friction and wear that dominate the process (plowing, adhesion, oxidation, etc.) and to any chemical reactions that may be taking place. Most surface-surface interactions are poorly understood, making the additional modeling of surface texture even more difficult. A relatively new and untested use of micro texturing, that uses fields of micro textured surfaces to replace macro-scale geometry, may also provide benefits. All of these mechanisms have the potential to reduce friction and wear, increase load capacity, and increase lifetime in numerous applications, but extensive research still needs to be performed to further define and explain the mechanisms, and means by which to optimize the use, of surface micro texturing.

They shows that all textured samples have a lower wear amount and surface roughness, and a smaller wear debris than the non-textured sample after the 7 h test. The wear amount of the 5% dimple area fraction sample is approximately 72% less than that of the non-textured sample. All results indicate that the surface texturing substantially affects the wear reduction and that the 5% dimple area fraction sample tends to yield the minimum wear as well as better wear topography. The surface texturing of the sliding surface is important in reducing friction and wear. To explain the mechanism responsible for these reductions of the surface texturing, the effect of the different dimple area fraction on the hydrodynamic lubrication under sliding contact is evaluated, and according to Refs. [2, 18, and 12] the average pressure distribution of the fluid film is chosen as an index to evaluate the effect of the hydrodynamic pressure generation on the surface texturing; the results are shown in Fig. 7. Fig. 7(a) shows that normal to the sliding directions, the hydrodynamic pressure is strongly influenced by the adjacent dimples and the interaction between the adjacent dimples become significant with increasing dimple area fraction, the similar results are also shown in Ref. [24]. Because of this interaction, the pressure does not decrease to zero along the width boundary, thereby indicating that the interaction between the dimples significantly affects the hydrodynamic pressure distribution. Fig. 7(b) shows that all textured samples can generate greater hydrodynamic pressure compared with the non-textured sample and will thus increase the load carrying capacity. During the friction, hydrodynamic pressure is generated in the narrow gap between the mating surfaces. The load carrying capacity can be provided by each dimple because of an asymmetric hydrodynamic pressure distribution over the dimples that results from local cavitation in the diverging clearance of the dimples [11]. Fig. 7(b) also shows that the 5% dimple area fraction sample generates the greatest hydrodynamic pressure of all the dimple area fractions and thus yields maximum load carrying capacity. According to the numerical analysis and the experimental results, the generation of the surface texturing's hydrodynamic pressure is crucial to reducing friction and wear, and 5% is the optimal dimple area fraction value for achieving minimum friction and wear, which is consistent with the previous study results in Ref. [12]. Additionally, the dimples on the surface also serve as traps for the wear debris and as micro-reservoirs for lubricant retention, thus reducing the ploughing and deformation components of friction and wear.

Conclusions

Surface texture parameters were reviewed based on their tribological performance indicators, and a considerable section of the literature demonstrates that surface textures are very effective at friction reduction. The performance of textured surfaces were found to depend on both texture parameters and on the conditions used in experiments. Experimental conditions included the types of material, sliding speeds and directions, lubrication, normal loads, and surface roughness and material properties including hardness and wettability. On the other hand, texture parameters were as follows: shape, diameter, height, and area ratio of dimpled surface; width, depth, angle, and area ratio of grooved surfaces. The effect of textured surfaces on wear reduction was not yet fully demonstrated because of the occasional difficulties in the wear monitoring process. However, few articles demonstrated that a wear rate can be limited by more than 50% by using a suitable and well-defined dimpled surface. Other performance indicators included thicker fluid film thickness and reduced participation of wear debris. A number of manufacturing processes were identified as able to generate well-defined micro textured surfaces.

Author contribution

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Competing financial interests

The authors declare no conflict of interest.

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