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A Review of Surface Texturing in Internal Combustion Engine Piston Assembly

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Abstract: This paper presents a brief review of surface texturing with a focus on piston assembly application. The paper begins with a general discussion on surface texturing and the manufacturing process of micro dimples. Further, it discusses the theory of hydrodynamic lift generation and the effect of parameters of micro dimples texture on the surface-to-surface friction. Finally, the effect of surface texturing on heat transfer is briefly discussed. In pursuits to improve internal combustion engine (ICE) efficiency, tribological improvement of moving surfaces by means of micro surface texturing seems to be one of the way. However, texturing parameters have to be carefully designed as it can cause detrimental effect if the designs are wrong. Studies has shown micro surface texturing at piston ring could reduce friction around 20%-50% compare with un-textured piston ring and also reduce fuel consumption at 4%. Micro Surface texturing could also improve heat transfer between the surfaces to reduce piston slap and lubrication oil temperature. As reports on the surface texturing on friction reduction and heat transfer improvement in piston assembly are relatively scarce, it is suggested that optimization of micro dimple parameters for piston skirt application and its effect on engine tribology and heat transfer characteristics to be further investigated.

Keywords: Surface texturing; piston assembly; tribology; heat transfer; micro machining

1. Introduction

Fuel efficiency and higher engine efficiency demands have put the researcher's attention towards more efficient engine research since the first development of the internal combustion engine. Many works have been done to improve engine performance and fuel economy in various ways. One of the approaches is to improve the tribological performance of an engine such as friction losses. It was estimated about 11.5% of fuel energy is used to overcome engine friction [1-3]. In an internal combustion engine, roughly about 50% of friction loss contribute by piston assembly, valve train by 25%, crankshaft bearings 10% and engine accessories by 15% [4-5]. These components are the most lubricated component in the internal combustion engine, which has always been designed to be less in mass and friction and at the same time not compromising its durability and reliability [6]. Since most of the friction loss happened at piston assembly [5, 7-9], this aspect has been the focus of the researchers in the past decades to improve the tribological performance of an engine [10]. Within piston assembly components, friction is mostly contributed by piston rings [11-12] and piston skirt [6, 13-14]. According to Littlefari et al. [14], 3% from fuel energy is used to overcome frictional losses in the piston to cylinder liner assembly and further 4% from piston rings [15]. Furthermore, controlling friction as well as wear in piston rings and skirt [1, 16] will determine the lifetime of the components [7], fuel economy, and engine performance [12] as well as to meet the strict CO2 emission legislation [9].

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Another concern is that piston skirt significantly contributes to the generation of piston slap noise [3]. Therefore, the piston skirt has always been designed with minimal friction with the smallest slap noise and to maintain its durability and reliability. However, a trade-off between slap noise or piston secondary motion and lubrication [17-18] has always been a research topic in improving tribological performance. Piston slap noise is due to high clearance between the cylinder liner and piston skirt. However, lowering the clearance may reduce engine performance because of viscous shear friction [19].

Heat is another factor to cause frictional losses of an internal combustion engine. Hamid et al. [20] reported that high-temperature combustion gas together with adiabatic shear heating [21-22] of the piston is the cause of reduced oil film thickness and it is the main cause of frictional losses and piston wear at high engine speeds [23]. The heat from combustion gas will eventually transfer to a lubrication oil film around the piston. Some of the generated heat due to adiabatic shear heating from Newtonian oil film lubricant will remain in the oil film and the temperature of the lubricant oil continues to rise and significantly affects secondary motion of piston, oil film pressure, oil film thickness and viscosity [23] as well as causing lubrication oil leakage [24]. According to Harigaya et al. [22], as the shear rate between a piston ring and cylinder liner increases, the viscosity of lubrication oil will reduce as it is affected by the oil film temperature and shear rate. Then, the oil film thickness will decrease as oil viscosity decreases. This will affect lubrication oil load carrying capacity, friction loss, piston wear and piston secondary motion [20] and lastly will be the cause of engine failure [21]. While this drawback can be reduced by using synthetic lubrication oil [25], another method to improve this issue is highly desirable.

Surface texturing has been found to be effective in improving the tribological performance of sliding contact surfaces [26-28]. In the internal combustion engine, surface texturing has long been implemented by cylinder liner honing [11, 29]. Until now, a lot of studies has been done to improve tribological performance with surface texturing not only in automotive but also in mechanical seal, bearings and cutting tools [8, 26, 29-30].

Studies have shown that textured piston rings are able to reduce friction around 20-50% in comparison with non-textured piston rings [8]. Ryk & Etsion [12] performed experimental study to investigate the partial texturing effect on piston rings. The result showed that partially textured piston rings were able to achieve around 25% reduction in friction. In Tomanik [9], a significant rise of hydrodynamic pressure was seen with micro dimples on piston rings and cylinder bore. According to Etsion & Sher [11], 4% lower fuel consumption was found with partial laser surface textured piston rings while no change was seen in the exhaust gas composition or smoke level. Nandakumar et al. [31] conducted a study to regain compression in an old engine with laser surface textured piston skirt at major thrust side and found out that the textured piston gained a 60% improvement in compression, regained fuel efficiency and performance as well as a reduction in HC and CO emissions. Moreover, the piston slap noise was reduced by 8 decibels and engine oil consumption was also significantly reduced.

2. Micro Dimples Texturing Benefits

Surface texturing can improve the tribological performance of the contact surfaces with friction and wear reduction. Surface with texture will decrease its contact surface and therefore reducing friction between the contact surfaces [32-33]. Friction can be reduced by up to 30% with a distribution of micro dimples on the surface where it functions as lubrication reservoirs and provides lubrication in starved lubrication condition to support lubrication components [33-36]. The ability to act as a lubrication reservoir with microstructures on the contact surface also was found in the work of Basnyat et al. [37] and Voevodin and Zabinski [38]. The lubricant in the micro dimples (reservoir) will be brought up to spread through the surfaces during sliding of those surfaces [8].

Surface textures such as micro dimple were also found to entrap wear [12, 26, 30, 39-42] in either dry sliding or lubricated surfaces [11]. This wear entrapment can reduce wear by containing wear debris that exist between contacting surfaces. In the non-textured surfaces, this debris will cause high contact stress and cause the increase of friction and wear of the components [8], thus, reduce the lifetime of the components. Fig. 1 shows how surface texture can entrap wear debris with a sliding ball on a plate. Fig. 1(a) shows wear debris trapped the wear debris inside the texture cavity and therefore reduce wear while in Fig. 1(b) shows the wear debris on the non-textured surface causing high contact stress thus increase friction and wear as the ball slides [8]. In Gropper et al. [26], a textured surface can lead to a decrease of stiction [32] which can reduce wear and therefore increase durability.

While surface texturing can be capable of as lubrication reservoir and trapping wear debris, the most prominent effect of surface texturing is its ability to generate hydrodynamic lift which enhance load carrying capacity, reduce friction coefficient, and increases oil film thickness. Lubrication at piston cylinder liner and piston skirt is categorized as a hydrodynamic bearing system where the load-carrying capacity of the piston skirt is the effect of the integration pressure distribution [43]. In full or mixed lubrication conditions, micro dimples texture on a surface can function as micro hydrodynamic bearings [29] and generating hydrodynamic pressure very well [33, 44-45]. The generation of additional hydrodynamic pressure can cause a certain increase in load-carrying capacity [26].

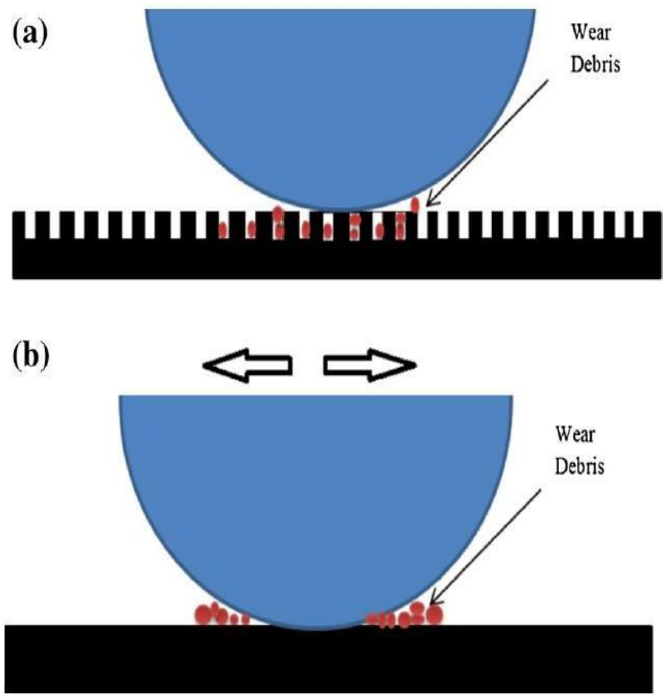

Fig. 1 - Cross-sectional view of reciprocating ball on a plate in lubricated condition. (a) Textured surface; (b) untextured surface [8]

3. Micro Dimples Fabrication Methods

The requirement of micro shape, features, and parts has been demanding in the various fields [46]. Therefore, micro-manufacturing methods to fabricate micro textures on surfaces have been widely investigated and researched. Some of the methods are laser surface texturing (LST), micro-electrical discharge texturing (EDT), micro electrochemical machining (ECM) and micro-mechanical cutting such as micro-drilling, micro-milling, and micro-turning. Fabrication of micro dimple array with high quality and dimensional accuracy is very crucial [47-48] as it will affect the tribological performance of the surface. As every manufacturing method have their advantages and limitations, proper selection is very important according to the micro-texture applications. At present, research regarding tribological performance and surface integrity of produced micro-texture with various micromachining towards its intended applications are still limited and require more extensive research.

3.1 Laser Surface Texturing

Laser surface texturing is believed to be the most promising method in fabricating micro-texture on surfaces [11]. LST is a process to remove materials from the surface with rapid melting and vaporization of high energy laser pulses [49]. This method is known for its flexibility [50] since it is fast, short process time, environmentally friendly, able to control the shape and texture size [29] and producing complex shapes [11] which permit the establishment of optimum design. However, according to Ghani et al. [51], LST is restrained by its high process time, high cost involves more post-processing and the processing material only limited to non-transparent [50].

The LST method has been extensively studied and improved over the years in producing micro-texture. In 2006, Voevodin & Zabinski [38] has explored the use of UV pulsed laser which become possible at that time for tribological surface topography alteration. In comparison with an infrared laser, the solid-state pulsed UV laser is less expensive, faster and can reduce surrounding surface overheating. Research by Luo et al. [52] has improved the efficiency and quality of CO_2 LST by using beam moderating system based on rotating polygon and able to achieve a nearly circular shape of a micro dimple. Ezhilmaran et al. [30] uses narrow pulsed width LST at 5-6 nanosecond using Q switched, pulsed Nd^{3+}: YAG laser which is opposed to usual LST method that is using pulse width ranging around few hundred nanoseconds. Furthermore, this method could utilize shorter wavelengths with the increase of light absorption by a metal thin film that could reduce the heat-affected zone.

Another alternative of LST is laser shot peening (LSP). Guo & Caslaru [49] used micro LSP together with automatic XY table and demonstrate a reliable method for fabrication of micro dimple arrays with enhanced surface integrity. The LSP experiment on polished Ti-6A1-4V surfaces shows that the center of the peened dents has the highest hardness and high compressive stress.

Laser surface texturing has been extensively researched for textured piston rings by Etsion's group for its effects on tribological and engine performance. A few works published by his group shows that LST piston rings were able to reduce average friction force [53], reduce friction coefficient and its effect is more significant at high speed, load, and viscosity oil [41] and achieve fewer fuel consumptions [11]. While at the piston pin, LST was able to improve scuffing resistance [54].

3.2 Electrochemical Machining (ECM) & Electrical Discharge Machining (EDM)

Electrochemical machining (ECM) and Electrical discharge machining (EDM) provides an exceptional way to produce a 3D complex shape features and component (micro and macro) for hard to machine materials such as steel, carbides, titanium alloys and super alloys such as Inconel [55-57], and suitable for conductive and nonconductive materials [46]. Furthermore, because these processes are a non-contact process, it will prevent tool deformation and breakage and therefore suitable for micromachining that is using small size tools [46]. Many studies have been done so far to improve the efficiency of these processes and producibility of uniform micro dimples to be applicable in the industry.

The process of ECM involves the electrochemical dissolution process where it removes electrically conductive materials on a work piece [58]. The advantages of ECM are that it lacks residual stresses and heat-affected layer, not having tool wear issues and able for large area machining [59]. However, the main issues of this process are that it requires the texturing work piece to be masked individually which increase the process time and cost [60] and also the quality of individual dimple [61]. Many of the studies recently focus on producing micro dimple array instead of single dimple [62]. Many technics have emerged such as maskless electrochemical texturing (MECT) [60, 63], through-mask electrochemical micromachining (TMEMM) [58, 62, 64-67], using Polydimethylsiloxane (PDMS) mask [59, 61, 68-71], sandwich-like electrochemical micromachining (SLEMM) [72-73] and others [74]. Chen et al. [69] had applied the ECM method with TMEMM technic together with a PDMS mask and successfully produce micro dimple array on a cylindrical surface. These studies show improvement in friction coefficient [64, 74] and wear [60] with fabricated micro dimples as well as able to produce a different type of micro dimple shapes [63, 60-61]. However, there is still a lack the studies of tribological behavior of ECM produced micro dimples.

The electrical discharge texturing (EDT) method has been known to be suitable to mass produce texturing on a surface and currently being used to texture aluminum sheet for automotive industry application [75]. EDT is an electrical discharge process between the work piece electrode to remove material. The tool electrodes melt and vaporize materials due to the high frequency of electrical charge [76]. Electrical discharge machining (EDM) allows significant benefit compared to mechanical cutting machining. EDM is able to fabricate smaller feature dimensions (less than 100mm), complex geometry structure, smoother surface, lower machining force and avoid mechanical stress on a work piece. However, EDM also possesses some limitations such as low material removal rate [56-57], small value roughness, re-solidify of molten material on the surface and unable to conform work piece dimension because of the tool do not come in contact with the work piece. For the micro-EDM process, there are different types available such as micro-wire EDM, micro-electric discharge milling, die-sinking micro-EDM and micro-electric discharge drilling [76].

Liew et al. [77] fabricated high accuracy micro dimples in short process time using ultrasonic cavitation assisted micro-electrical discharge machining with carbon nanofibers to produce microstructure on reaction-bonded silicon carbide with a good surface finish. Kumaran et al. [78] studied dimple formation on titanium alloy varying micro EDM parameters. They produced micro dimples with optimum settings able to achieve smooth wall and enhanced accuracy. Roy et al. [79] used Reverse Micro Electrical Discharge Machining (RMEDM) where this technique allows high aspect ratio single or multiple 2.5D features with a different cross-section. The author utilizes the limitation of the process which is the effect of secondary and higher-order debris erosion to produce 3D hemispherical shaped micro-texture. The study found that this method was able to achieve 5 times material removal than normal RMEDM.

Some of the studies in EDT micro dimple tribological behavior were carried out by Zhou et al. [75]. In the study, micro dimples on aluminum sheet produced by EDT method were able to reduce friction coefficient at high contact pressure (higher than 64Mpa) but at lower contact pressure (lower than 64MPa), the friction coefficient is reduced. Furthermore, the sliding directions could also affect the friction coefficient. The lower friction coefficient was found when the sliding is along the sliding direction than in transverse direction for low contact pressure. However, for higher contact pressure, the friction coefficient was found higher along the sliding direction than the transverse direction. Liew et al. [77] further studied the EDT method on tribological behavior using the electrical discharged machine under boundary and mixed lubrication condition. The result shows that micro-EDM dimpled specimens obtain 11-27% lower friction coefficient than un-textured specimens and also found that round dimple geometry gives lower friction and wear than diamond and ellipse-shaped dimple. Zavos & Nikolakopoulo [80] fabricated micro textures with a width of 1,000mm and a depth of 4mm in order to enhance friction and wear of piston ring/cylinder assemble using EDM process. The study found that enhancement in oil film thickness at about 27%.

3.3 Mechanical Cutting Machining

Another group of micro-manufacturing process is micromechanical cutting [81]. According to Boswell et al. [81], micromechanical cutting is the process where the material is chipped or ground off to create the desired shape. It uses a physical cutting tool with a high precision machine to fabricate shape and features in micrometers [82]. Micromechanical cutting process also cost-effective and relatively fast compared to other non-traditional techniques [83]. Micromechanical machining also able to machine any machinable material, fast process planning, and able to produce three-dimensional geometry where it is limited by the machine and tool used [82]. There are 3 major types of mechanical machining which are turning, milling and drilling. The micro turning process provides a very good surface finish due to the use of diamond cutting tools where it's made possible to machine almost any type of material. However, the drawbacks of this process are the tools is constantly gaining heat from cutting friction [81-82] and pressure, as well as the issue of tool breakage [81]. Micro milling has been shown to have better accuracy and having a material removal rate of up to five times of micro-EDM [84]. Micro milling is also a very flexible process that able to perform various machining and fabricate many complicated and detailed shapes and features and at the same time meet strict surface finish and dimensional tolerance [81, 85]. The issues with micro-milling are controlling cutting forces and accuracy and the tools facing large amounts of wear which reducing the accuracy [81, 86]. While for micro-drilling, the process is very efficient in producing much deeper holes compare to other drilling technique but the process is not possible for flat bottoms. The major concerns regarding this process are the breaking of the micro tool drill and vibrations due to drill suffer from excessive wear and fracturing [81]. Another major issue with micro-drilling is that the microchip builds up during the drilling process is not fully remove from the hole which will affect the whole surface [49, 51, 82].

Greco et al. [87] have used vibro-mechanical texturing (VMT) as a surface texturing method. This process is based on the turning process and performed on a standard computer numerical control (CNC) lathe and fitted with a piezoelectric-actuated tool positioning stage. Vibratory motion or tertiary motion generator (TMG) is controlled at the tool and cut micro-sized dimples on a work piece. The author also acknowledges the process is versatile, accurate and cost-effective. Guo & Ehmann [50] proposed a new designed resonant mode of 2D tertiary motion generator that able to produce required elliptical trajectory at an ultrasonic frequency. The device operates in resonant mode with tangential and normal vibration almost as same as the resonant frequency. Chen et al. [88] developed a reciprocating fast tool feeding mechanism using an elliptical cam drive for the rapid fabrication of micro-texture arrays on the surface. The elliptical cam operates as the drive mechanism for the reciprocating feed tool system. This design having symmetrical structural able to withstand vibration making it stable for high acceleration motion and its respond speed twice compare with other tool systems. Using this technique, micro dimple array of 12x34 is quickly done at the drive frequency of 10 Hz, work piece speed of 1200 mm/min, cutting depth of 30 μm, and processing time of only 40 s. The resulted micro dimple array feature is very consistent making this technique very suitable for highly reproducible and precise dense micro-texture. Tribological analysis study performed by Ghani et al. [51] and Abdul Rahman et al. [89] employed an in-house developed dynamic assisted tooling (DATT) for turning process in fabricating micro dimples array with different dimples parameters and Reynolds number. The study in Abdul Rahman et al. [89] shows that fabricated micro dimples able to improve load-carrying capacity compare with the untextured surface while in Ghani et al. [51], fabricated dimple array with varying dimple parameters able to achieve up to 56% friction reduction compares to non-textured surface. No microstructural change has also been found at dimple machine surface and surface roughness at dimple and non-dimple area. With this study, Ghani et al. [51] recommended the turning process in micro dimple fabrication for industrial manufacturing as this process capable of preserving material properties and environment-friendly process.

Roy et al. [48] fabricated well defined micro dimple pattern on an Al2O3 surface using drilling CNC micro machine. Mechanical analysis was conducted and found that there is a change in hardness, toughness and residual strength while no foreign wear debris was found. Tribology test also was done and a significant reduction in friction coefficient obtained from the fabricated micro dimples. Matsumura & Takahashi [90] studied the milling method for machining micro dimple with an inclined ball end mill. In Matsumura et al. [91], a novel machining method has been proposed to fabricate dimples on cylindrical surfaces in whirling, which usually use for machining threads such as ball screws. The process involves the rotating work piece and tool mounted on a whirling ring. A mechanistic model of dimple machining is used to control dimple shapes.

4. Hydrodynamic Lift Generation

The most accepted theory of the hydrodynamic lift for the textured surface was proposed by Hamilton et al. [35]. The theory suggested that the hydrodynamic lift is caused by the cavitation phenomenon. Cavitation phenomenon can be defined as in an isobaric region when the pressure is lower than fluid vapor pressure, cavitation (bubbles) will occur, and in this case, it appears in the texture region. This mechanism can be seen in a single texture without cavitation at a sliding surface which will cause an antisymmetric pressure distribution over the texture where pressure decrease in divergence section and increase in convergence section of the texture as shown in Fig 2.When cavitation occur, cavitation will offset the antisymmetric pressure distribution at the texture and creating total positive pressure thus creating hydrodynamic effect [8, 26, 35]. The cavitation phenomenon has been sighted with high-speed cameras in an experiment by Qiu and Khonsari [92-93] and Zhang and Meng [94].

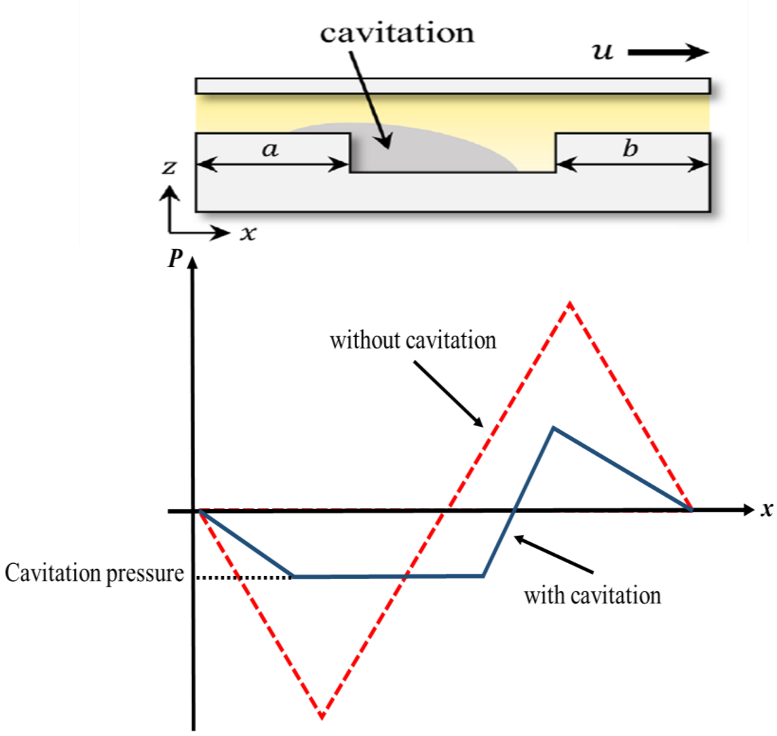

Fig. 2 - Cavitation in a single texture cell and the pressure distribution [26]

According to Gropper et al. [26], a hydrodynamic lift can only occur when the cavitation pressure is lower than the supply pressure because of the required pressure gradient exist to make sure enough lubrication supply. In case of supply pressure and cavitation pressure are equal, the pressure gradient does not happen which result in starvation in the dimple and no pressure can be generated. Furthermore, when the supply pressure is much higher than cavitation pressure, cavitation will not happen as the pressure distribution over a single texture is antisymmetric and lift could not occur.

Another mechanism for the hydrodynamic lift occurrence was proposed by Tønder K. [95-97]. Tønder suggested that the texture or roughness area of a parallel sliding surface acts like an inlet step that similar to Rayleigh step bearing [8, 26]. The similar concept also found by Etzion's group which is called collective dimple effect. The concept explained that the texture inlet has more than average film thickness than the non-textured outlet thus the partially texture surface act similar to Rayleigh step bearing [26, 95-97]. This concept is shown in Fig. 3 which shows pressure distribution over the partially textured slider for three cases. The first case is cavitation does not occur when supply pressure is much higher than cavitation pressure (Pcav << Psup), second case is cavitation happens in the first two dimples when supply pressure is higher than cavitation pressure (Pcav < Psup), and lastly the third case where the cavitation happens in all dimples when supply pressure is equal to cavitation pressure (Pcav = Psup). From Fig. 3 can be seen that significant load support can be generated even cavitation does not occur at all (Pcav << Psup) which shows that cavitation, not the only mechanism to cause load support mechanism [26]. Tønder K. [95] also found that there is resistance towards the texture region to reduce leakage of the fluid.

The work by Arghir et al. [98] found that the relation of inertia in generating lift force on the flat wall. This was discovered by solving the full Navier-Stoke equation for different macro roughness cells [26]. Later, Sahlin et al. [99] further studied the effect of inertia towards grooves patterned surface of two parallel walls in hydrodynamic lubrication condition and shows that the production of load carrying capacity is mainly because of fluid inertia [26]. However, a study by Dobrica and Fillon [100] shows an opposite effect where inertia could bring negative effects towards load carrying capacity [26]. There are few more studies regarding the inertia effect with different types of application of textured surface [26] and the understanding of this mechanism is still developing and uncertain.

Until today, the mechanism to cause pressure build-up or hydrodynamic lift still being studied as the cause for this may due to the influence of various operating conditions, parameters and more than one mechanism which being briefly discussed above depending on the application it is used [8][26].

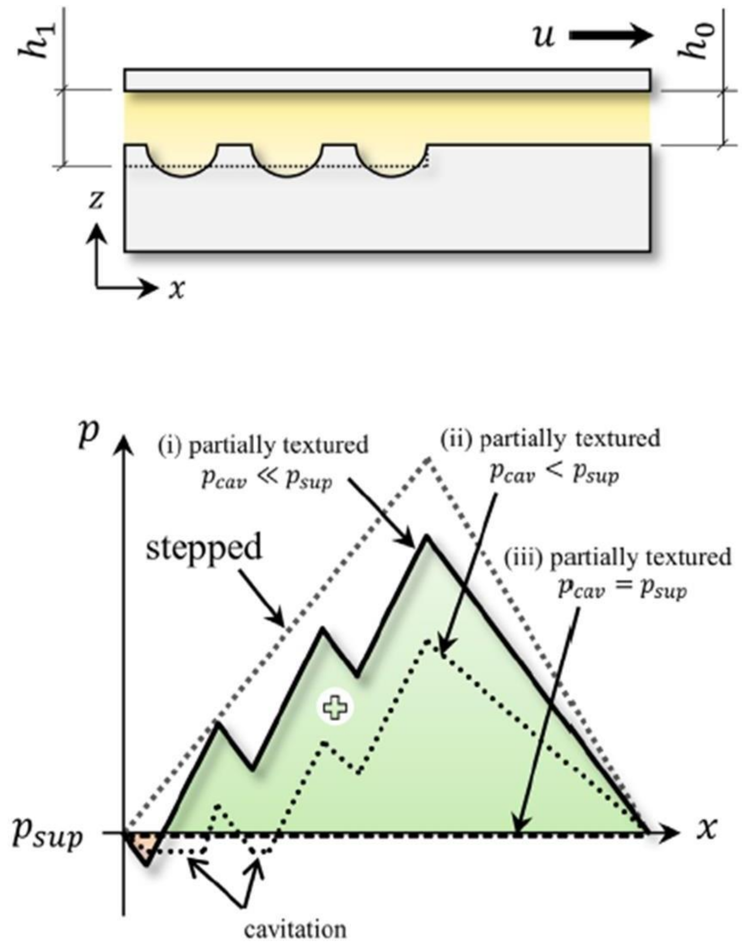

Fig. 3 - Pressure distribution overstep textured slider [26]

5. Groove Texturing

Piston skirt used to be designed with deep cut grooves for oil retention to help in the mixed lubrication condition. However, the grooves became detrimental to the formation of hydrodynamic oil films at the piston skirt and cylinder liner surface. Because of this, now piston skirts are designed to be smooth [6]. According to Nakano et al. [45], groove pattern prevents the development of hydrodynamic pressure and because of that, the lubrication condition become boundary lubrication condition thus led to higher friction coefficient while dimple structure produces lower friction coefficient, improving load-carrying capacity and lubrication film became thicker.

Aoki et al. [101] conduct a numerical study for the lubrication performance of grooves fabricated by the machining process on the piston skirt surface. The result showed that by increasing grooves density and shallow grooves can be efficient in decreasing friction coefficient. However, the study by Fang et al. [3] which also studies the effect of groove textured piston skirt indicates that higher groove density is useful to reduce viscous shear friction but unfavorable for continuity of build-up pressure distribution in the convergence region. The study also shows that a deeper groove is better to reduce friction at higher engine speed but at a slower speed, the effect is detrimental as the wear becomes worst. The study by Biboulet et al. [102] which did a numerical analysis of pressure distribution and load-carrying capacity of groove textured cylinder liner against two type of piston rings which has small and large radius of curvature shows that the groove cannot be too dense to obtain the optimum load carrying capacity but enough to have a groove below the ring. The deep grooves also producing maximum pressure perturbations with a higher load carrying capacity compared with the shallow grooves. In terms of groove shape, Fang et al. [3] and Biboulet et al. [102] agrees that it’s not giving a significant effect toward lubrication performance. These study by Aoki et al.; Fang et al. and Biboulet et al. [3, 101-102] show the effect of grooves parameters are very dependent towards the surface applications.

6. Micro Dimples Texturing Parameters

Parameters involving surface texturing can be categorized into texture geometry which are shape, size such as depth and diameter and texture shape orientation for unsymmetrical shapes. Another parameter can be said as parameter relative to the surface such as aspect ratio or depth to diameter ratio, density or texture per unit area and texture position of placement [8, 26, 30, 89]. These parameters have been studied extensively over the past years to obtain minimum friction, minimum leakage, maximum film stiffness and maximum load-carrying capacity [29]. According to Gropper et al. [26]; texture density, dimple aspect ratio, relative dimple depth producing the most effective and therefore are the most important parameters for texture design. The optimum texture parameters seem to be depending on their type of contact and operating conditions thus, the design of the texture have to consider these conditions to avoid detrimental effect [8, 26].

6.1 Dimple Shape, Placement and Orientation

Various texture shapes have been studied before such as circular, triangular, diamond, square, hexagon and elliptical [7-8, 44, 103-104]. Fig. 4 shows some of the texture shapes. However, for the unsymmetrical shapes like elliptical, rectangular and triangular, the orientation of the shapes can also give different results. The tribological performance can be improved if the unsymmetrical dimple shapes major axis side to be placed perpendicular to the sliding direction [8, 105].

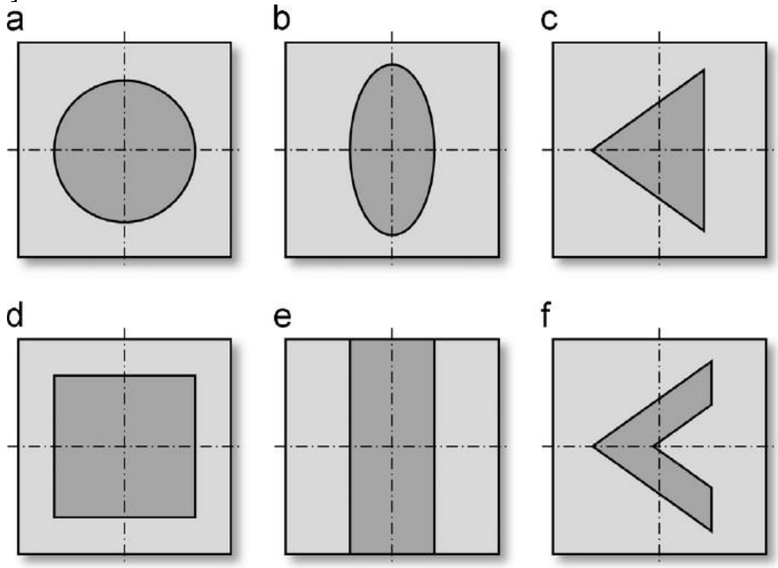

Fig. 4 - Texture shapes. (a) circular; (b) elliptical; (c) triangular; (d) rectangular; (e) groove and (f) chevron-like [26]

In simulation by Yu et al. [44] to study the effect of a single dimple in circular, elliptical and triangular shape on pressure generation using Reynolds equation and periodic boundary condition finds that elliptical dimple where the axis is perpendicular to the friction direction provides the best load carrying capacity among the three shapes [26, 89]. Fig. 5 shows the simulation result by Yu et al. [44]. However, when the triangular (Fig. 5(b)) and elliptical (Figure. 5 (d)) shaped placed parallel to the sliding direction, the load-carrying capacity effect is smaller compared to a circular shape. A similar finding also found in [93, 104, 106]. A pin on disc experiment done by Liew et al. [7] which studies three different dimple shapes which are diamond, circular and elliptical conclude that circular dimple gives lowest friction coefficient followed by diamond and lastly elliptical dimple. However, to be noted that the elliptical dimple in this experiment was placed parallel towards sliding direction thus gives the lowest value. Grooves, circular and chevron-like dimple shapes were experimented under reciprocating sliding hydrodynamic lubrication by Costa & Hutchings [107] shows that chevron-like shape which the apex pointing along the sliding direction gives the highest film thickness and the grooves give the lowest.

In Yu et al. [44], hydrodynamic pressure can be increased by changing the dimple placement distribution array from normal square array to shifting the column of the dimple to optimize α degree to the dimple line as shown in Fig. 6 [89].

Numerical investigation to study circle, diamond, square, triangle and hexagon-shaped dimple by Siripuram & Stephens [103] found that variation of coefficient of frictions is more towards size compared to the shape of the dimple. They also found that triangular-shaped dimple reduces side leakage compared to other shaped being studied [8, 103]

Besides dimple and grooves, a protrusion pattern also exists. However, comparing dimple and protrusion shape texture, dimple texture is a much better choice because the real contact surface for dimples is much larger and therefore the average contact pressure is lower as well as the wear. Dimple texture also has an advantage of to allow smaller leakage and better sealing compare to protrusion [29].

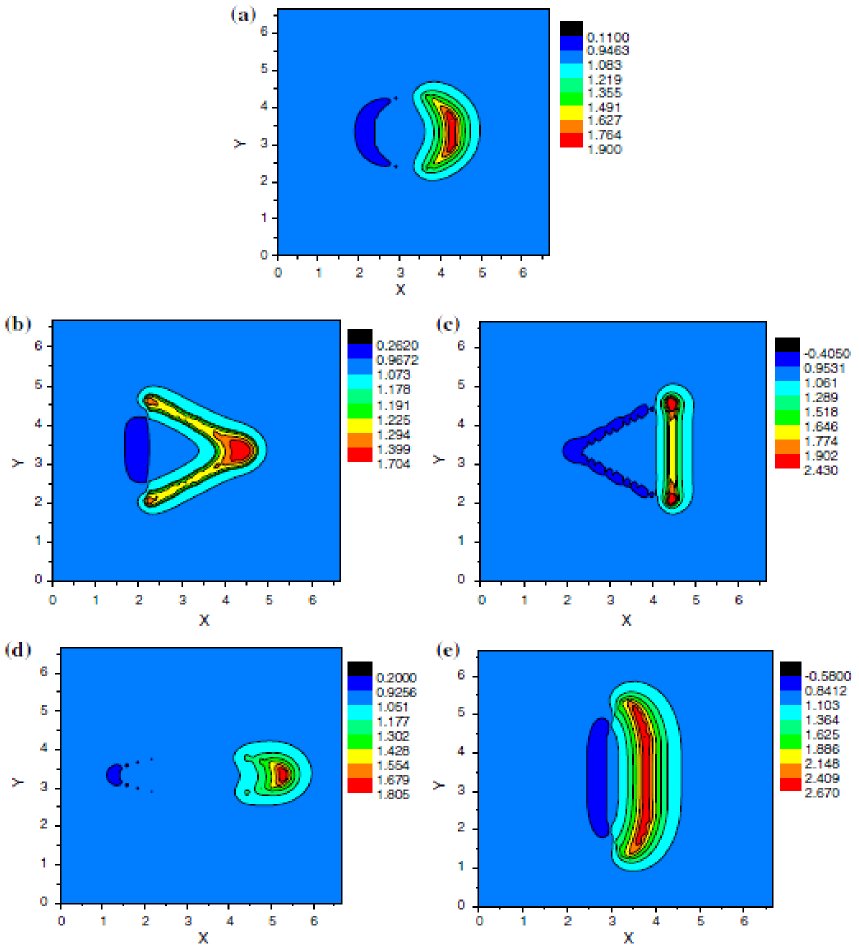

Fig. 5 - Dimensionless pressure distribution for varying textural shapes and orientations. (a) Circle; (b) Triangle (apex towards the sliding direction); (c) Triangle (apex opposites to sliding direction); (d) Ellipse (parallel to sliding direction); (e) Ellipse (perpendicular to sliding direction) [44]

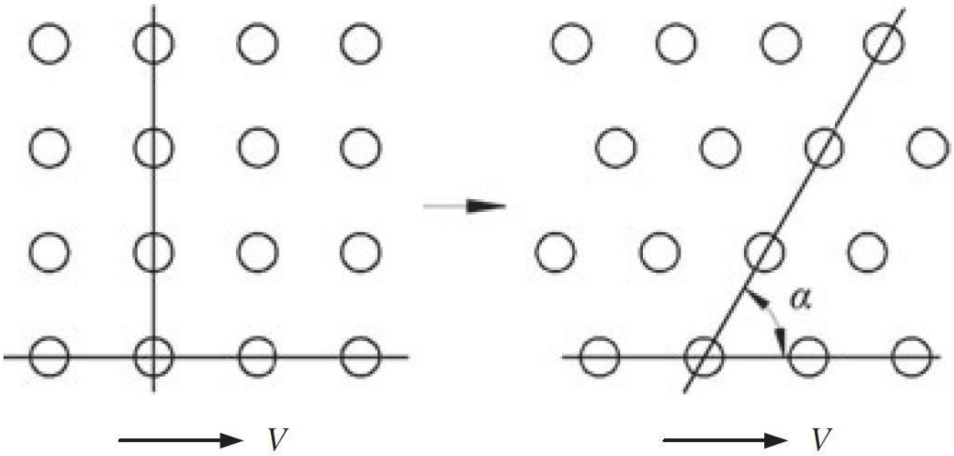

Fig. 6 - Dimple distribution array from normal square to shifted α degree array [44]

6.2 Dimple Diameter, Depth, Aspect Ratio, and Density

The diameter of a texture can be associated with aspect ratio and can affect the selection of density of the texture distribution on a surface [108-109]. However, when the texture density is high, the diameter of a texture does not change the average friction force and it will keep decreasing as the texture density increasing [53]. Kovalchenko et al. [41] shows that lower area density is more favorable for the lubrication regime transition. The theoretical model suggested that relatively high texture density is needed to obtain maximum load-carrying capacity. However, for a mixed lubrication regime, the stress concentration at the dimple edge needs to be properly addressed especially for high dimple density and for softer material as deformation could have happened which can affect hydrodynamic pressure and can cause wear on the material [105]. Dimple depth plays a significant role in determining aspect ratio and needs to be optimized. Dimple depth also shows higher importance than the dimple diameter in determining optimal dimple shape [110]. According to Han et al. [111], the optimum dimple depth depends on the width of the dimple and Reynolds Number to obtain maximum load-carrying capacity and minimum friction force. Low dimple depth can provide improvement in tribological performance while high dimple depth can cause a detrimental effect. In conformal contact conditions, deep dimple can cause a detrimental effect on friction and wear. This is because, when the low lubrication condition exists, the deep dimple will micro traps the lubricant and the lubricant will become concentrated around the dimple. Therefore, the hydrodynamic effect of the micro hydrodynamic bearing will affect only the small area and space between the surface decrease and friction and wear will increase [8]. An Orthogonal experiment by Yan et al. [112] suggested that the most important parameter affecting friction coefficient is dimple density, follow by dimple depth and dimple diameter for low-speed condition and the order could have changed according to the operating condition. According to Etsion [29], the most important parameter for full fluid film lubrication is aspect ratio where this parameter can be optimized to obtain maximum load-carrying capacity and oil film thickness as well as minimum friction coefficient, and another important parameter is dimple density which also needs to be optimized. Aspect ratio and texture density are an important parameter to improve tribological performance, hence diameter parameter has always been studied together with aspect ratio and texture density [8].

Ezhilmaran et al. [30] conduct an experimental on dimpled piston ring surface to study the tribological effect towards dimple diameter, aspect ratio, and dimple density. The study found that the friction coefficient decreases with an increase of dimple diameter until they stabilize at 80μm while maintaining its aspect ratio of 0.3. In terms of dimple density, 16% of dimple density shows consistently minimum friction even with changing the dimple diameter. The average film thickness also increases while increasing dimple diameter from 40μm to 80μm and further increasing dimple diameter will keep increasing film thickness but for low aspect ratio only. A pin on disc experiment done by Greiner et al. [113] to study the effect of velocity gradient towards friction by varying dimple diameter while maintaining dimple depth and density shows that with high-velocity gradient, smaller diameter between 50 μm and 70 μm gives the best friction reduction while for low-velocity gradient, friction decrease as diameter increase. This indicates that the dimple size has to be optimized for a given operating condition. Tripathi et al. [115] conduct ball on disc experiment on laser surface textured dimple on graphite cast iron to study the behavior of friction and wear towards dimple density and pitch while dimple size (diameter and depth) keeping constant. The experiment resulted that the highest friction reduction of 70% was obtained with 13% dimple density and 150 μm pitch compared with the un-textured specimen. The wear rate also decreases by 84% with the minimum dimple density being studied even though with its high surface roughness. Another pin on disc experiment was done earlier by Wang et al. that modified the test to be a cylinder rolling on a disk specimen with dimples to study the effect of dimple diameter while having the same dimple density and aspect ratio towards friction reduction. Wang et al. [34] also did simulations to study the effects of hydrodynamic pressure online contact conditions. The study indicates that only with the smallest dimple diameter of 20 μm, it was able to obtain friction reduction, and hydrodynamic pressure is highly affected by the radius of the cylinder to obtain hydrodynamic pressure greater than the non-textured surface.

7. Full and Partial Texturing

Full texturing and partial texturing have been studied over the years to increase the tribological performance of a contact surface. Full texturing as the name suggests, texturing all of its surfaces while for partial texturing, only utilizes a portion of its surface to be textured. Between full and partial texturing, partial texturing being considered is the best way to improve tribological performance [26]. A study by Kligerman et al. [53] shows that optimized partial texture piston rings give a significant lower value of average friction force than optimized full texture piston rings. This is because full texturing cannot provide enough hydrodynamic pressure as high pressure at the convergent region from the cavitation effect will be canceled out by individual dimple [8]. However, partial texturing gives a collective dimple effect similar to inlet roughness concept where larger average film thickness at texture inlet than non-textured outlet as found by Etsion’s group [11, 26, 89].

The position of the texture in the partial textured ring has been found that gives an insignificant effect of tribological performance [8] such as the work by Kligerman et al. [53] which found that there are very few changes in friction force by altering the position of texture from corners to the middle of piston ring. However, other studies showed differently. A study by Tomanik [9], suggests that the position of partial texture for the oil control ring should be in the middle to decrease the chances of dimple causing flakes at the corner surface [8]. While pin on disc experiment by Codrigani et al. [110] shows that partial texturing at the front half of the pin (inlet region) gives better tribological improvements than whole pin texturing or back half of the pin. The studies above show that the effect of texturing position still not clear and require further research.

Asymmetric texture shape such as chevrons and ellipse are preferable to improve load-carrying capacity and friction reduction where these shapes are performing better than usual selected circular shape for full texturing while for partial texturing, rectangular shaped dimple with flat bottom profile and maximal texture density is preferable to give optimal stepped bearing effect [26].

8. Heat Transfer with Micro Textures

Heat transfer from combustion gasses to cylinder liner plays an important role in engine design as it affects engine efficiency, power, and emissions [115]. According to Sideri et al. [116], higher heat flux in the combustion chamber leads to lower indicated work thus reduce the overall engine performance and increase fuel consumption [117-118]. Furthermore, gas temperature and oxygen concentration are the main cause for Nitrogen Oxide (NOx) formation [119-120] and they also lead to unburnt hydrocarbon and soot. On the other hand, heat from hot gasses produced from combustion also transferred to the piston crown and conducted to the other parts of the piston such as piston rings, piston skirts, underside, and pin as well as other parts of the engine likes cylinder liner [121]. Heat transfer analysis by Satyanarayana et al. [122] shows that the highest temperature obtained on the piston crown and the lowest temperature at piston skirt for all compression ratios that were studied.

Piston slides on cylinder liner and in between the clearance fill a lubrication oil film. This small clearance increases frictional losses and secondary motion of piston [121]. The trends for a high-performance engine which to use lightweight moving parts in order to reduce inertial imbalance has led to the use of piston made of lighter and lower density materials such as aluminum [14]. Moreover, material such as aluminum alloy carry particular properties such as fairly high hardness, tensile strength and toughness, as well as possess high corrosion resistance. These properties meet the requirement by automotive industry to reduce fuel consumption without losing on safety [123]. However, piston made from aluminum alloy faces significant mechanical and thermal distortion due to its thermal expansion coefficient [14, 121]. The thermal expansion coefficient of aluminum alloy is 80% higher than the piston made from cast iron which leads to engine design differences between cast iron piston engine and aluminum alloy piston engine in terms of running and design clearance [121-122]. Piston thermal deformation is crucial in determining piston friction and piston slap [121]. Furthermore, Esfahanian et al. [121] also mentioned that alloy piston must not exceed more than 66% of its melting point temperature [124] at any point of the piston which limits the engine piston alloy temperature about 640K. As it is important to maintain high heat and temperature and reduce heat loss [125] at the combustion chamber to increase thermal efficiency [126], it is also important to control the heat and temperature rise at piston to avoid thermal and mechanical damage. Improving the heat transfer rate could be a potential way to control the heat at piston assembly.

A well-known method to improve heat transfer since the past decade is by surface texturing such as roughing the surface with random sand grain or with regular geometric roughness [127] and organized textures such as dimpled surfaces [128], rib and protrusions [129]. These textures perform to increase turbulence level and secondary flows to enhance mixing and, in some occurrence, forming streamwise oriented vortices. These vortices and secondary flows increase secondary advection of heat from the surface and also increase three-dimensional turbulence development by increasing shear and establish velocity gradients over the flow volumes [129] improving convective heat transfer. Besides increasing heat transfer by turbulence mixing [128] and secondary flows, surface texturing also increasing surface areas for convective heat transfer [129]. A study by Sato et al. [130] revealed that heat transfer performance highly leans on not only flow operating conditions but also thermo-physical properties of the working fluid as well as the importance of dimple designs such as dimple cavities with a suitable size to enhance turbulent heat transfer. Kim et al [131] in their work also agreed that surface texturing increased cooling performance as the result of increase surface area and turbulent mixing. However, extreme texturing could increase thermal resistance thus optimal setting was required.

Han et al. [127] and Han J. C. [132] had optimized heat transfer rates with different rib roughened surfaces parameters and operating conditions for fluid flow in channel. An investigation by Moon et al. [133] shows heat transfer enhancement with a convex patterned surface for heated air cooling. In the work of Kandlikar et al. [134], increasing surface roughness in small diameter tube increase heat transfer and Silva [128] founds that dimpled surface channel flow had improved heat transfer improvement maximum value around 2.5 times higher compared with a flat surface. The work of McInturff et al. [135] also shows an increase in heat transfer augmentation for impingement jet array cooling with small triangle roughness heated target plate compare with plain heated target plate. Karthikeyan et al. [136] has affirmed that surface roughness able to enhance boiling heat transfer as the surface roughness increases. According to Khonsari et al. [137], their stationary ring with dimples on its sidewall could reduce interface temperature by approximately 10% versus ring without dimples where this will lead to a reduction of thermal distortion and wear.

It is important to note that all these studies focus on moving fluid in channels and pipes while the application for mechanical contacts such as sliding bodies such as in piston rings and skirts, bearings and the cutting tool gives a different effect. In moving fluids, a textured surface may cause an increase in fluid flow resistance [127] thus increasing friction and lead to pressure drop [128, 132] but for mechanical contact application, surface textures can bring to reduce friction and increase in hydrodynamic pressure.

At present, there is still limited literature regarding the effect of heat transfer on textured surfaces or roughness on piston assembly especially on piston rings and piston skirts. Sagar et al. [126] optimized heat transfer rate aiming for power supplied optimization and efficiency of automobile engine using bodies with different roughness. The heat flux increases as the roughness of the body increase from 240 microns to 400 microns which indicates that’s heat dissipation increase when the roughness of the body increases for the same area and volume.

9. Current Research Trend

Many works on surface texturing currently were done as fundamental study that are mainly focus on either manufacturing processes to produce micro dimples/texture or, tribological performance of the micro dimples/texture. As different types of manufacturing processes have their own advantage and disadvantages in term of process time, cost and micro dimple producibility and consistency, thus make certain processes may not be suitable for certain applications with the limitations of material and shape of the intended application and intended dimple shape. On the other hand, tribological performance is also highly dependable on the applications which need to be correctly study and selected to avoid detrimental effects. Therefore, for any type of applications, these two factors have to be considered precisely.

There are also limited study of micro dimples surface texturing conducted on engine parts such as piston skirt, which received less to none attention despite its potential to reduce friction. Most study have focuses towards piston ring, bearing and mechanical seal applications.

To the best of our knowledge, in term of heat transfer effects of micro dimples for contact surfaces, there are still no studies carried out in this area. As heat plays an important role that affects the properties of lubricant and therefore affects the tribological performance, this area requires further consideration from researchers.

10. Conclusion

Surface texturing remains a potential method for improvement of the performance of contact surfaces in terms of reduction in frictions and wear towards industrial applications. It also improves heat transfer with an increase of surface area and generation of turbulence. At present, reported literature of the effect of surface texturing on friction reduction and heat transfer improvement in piston assembly applications is limited hence warrants further investigations.

From this brief literature review, some future scope of work can be suggested in the focus of piston assembly application:

1. Tribological study of micro dimple textured surface for piston skirt application which focuses on optimization of micro dimples parameters according to various engine operating parameters.
2. Tribological study of fabricated micro dimples with various manufacturing methods. Every manufacturing method has its own advantages and limitations especially in terms of the accuracy of producibility of the dimples and the effects on surface integrity.
3. Manufacturing process time and surface geometry suitability also have been the limitations for manufacturing micro dimple textures.
4. The effect of micro dimple texturing for heat transfer enhancement of piston assembly components has been very limited to none. Future studies also have to focus on different engine operating parameters to obtain optimize micro dimple design.

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