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Original Article

Experimental Investigation of Micro-Textured Piston Ring and Cylinder Liner Pair at Mid Stroke Operating Conditions

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Abstract *- It was utilized to study the micro-textured piston ring-cylinder liner interface tribological behavior at a constant speed, mimicking the mid-stroke state of an internal combustion engine using a linear reciprocating tribometer. The commercially available piston rings with spherical, square dimples and cylinder liner segments were used for the experimentation. SAE20W40 lubricant was supplied to the contact zone's inlet side. The temperature was 150ºC, and the load was varied from 80 N to 150 N in the trials. It has been observed that the rings with 300µm square dimples had good frictional resistance at 80 N load compared to the non-textured ring sample. The ring with a 150µm spherical dimple showed better frictional resistance at 150 N load than the non-textured ring sample. In general, 23.62% and 13.79% reduction in coefficient of friction was observed with 300µm square and 150µm spherical dimpled ring at 80N and 150N load, respectively. A better tribological behavior was found in the mid stroke operating circumstances for the textured ring and liner pairs than for non-textured ring and liner pairs working under a mixed lubrication regime.*

Keywords *- Piston ring, Cylinder Liner, Laser surface texturing, Wear, Coefficient of friction.*

1. Introduction

Researchers are focusing on friction and wear study between lubricated piston rings, especially compression rings, and the cylinder liner surface since the piston ring and liner pair create more frictional losses than any other engine component. It has been studied to improve the efficiency of an internal combustion engine with the help of maintaining a thin film in different lubrication regimes. When the piston ring is subjected to high loads during compression and expansion strokes, it wears out rapidly. The internal combustion engine works in a boundary lubrication regime during the initial span of the compression stroke and combustion stroke, which causes more friction and wear. Mixed lubrication regime was observed between the top dead centers and mid stoke as well as between the mid stroke and bottom dead centre, generally at high loads. Therefore analysis of the surface textured piston ring, and cylinder liner interface is a typical task for minimizing the overall friction of the interface.

Surface modification techniques are important in researching the tribological features of interacting surfaces like piston rings and cylinder liners (PRCL). A piston ring's textured surface may offer some lubricant when the sliding surfaces lack lubricant due to high loading conditions, as the lubricant is already stored there. The indentation in the textured surface may also operate as a place for trapping or accumulating wear particles, resulting in less wear when sliding. Surface modification is a good option to improve the sliding surfaces' tribological properties.

Researchers G. Ryk et al. have demonstrated the efficiency of micro-surface structure on piston rings and reported friction reductions of up to 40% in various piston ring arrangements. The textured dimples have a greater tribological impact when the dimple depth is optimal and the lubrication viscosity is low in contrast to fully laser surface texturing; partial laser surface texturing reduced friction in the test rig by up to 25%, according to Etsion et al. [4].

A study by Nathan Bolander et al. found that the depth of the dimple significantly affects the contact behavior of the two contact surfaces. Dimples with a diameter of 10 micrometers, compared to a diameter of 1 micrometer, are less effective in performance [5]. Exhaust gas composition was not considerably altered by laser surface texturing on the top piston rings of a Ford transit normally aspirated 2500 cm^3 engine at broad engine speeds under half load [6].

The tribological behavior of ring liner contact was explored extensively by Cong Shen et al. in a series of research. The pocket area ratio and depth have a substantial impact on frictional behavior. However, the effect of the pocket design is extremely limited. It is possible to reduce the friction of ring liner contact using a 25 percent area ratio and a 5 nm depth. When a pocket's area ratio or depth is great, friction isn't reduced [7]. To compare the effects of laser surface texture patterns on a non-textured cylinder liner surface on piston ring surfaces, the researcher Yali Zang and colleagues studied the rectangular and circular patterns of laser surface texture. Their findings found that the lowest average coefficient of friction across all texture patterns tested under running situations was in rectangular-shaped designs. [8].

An investigation into the tribological properties of piston rings with varying dimple sizes and aspect ratios, as well as various area densities, by V. Ezhilmaran et al., found that an area density of 16 % and 27% had the lowest friction of all the combinations tested [1, 18, 21]. Wei Haijun et al. used oil analytical techniques to examine the vehicle's piston ring and cylinder liner for friction and abrasion. A diesel engine's oil film generation, friction reduction, and run-in quality are all affected by the roughness grade of the engine's running-in oil and piston rings [10].

A reciprocating tribometer with a micro-textured ring liner system mimics a medium passenger car engine's functioning and reduces the friction coefficient in boundary and mixed-lubrication regimes. They also looked at the tribological effects of lubricant additives on the ring and liner system. For the dimples to affect tribo-chemical films, they had to remove any additives [11-12]. Sorin-Cristian Vladescu and his colleagues researched the effect of surface roughness on friction for a converging-divergent bearing operating in different conditions. They found that pockets that facilitate fluid entrainment minimize the amount of abrasion [13]. Arslan Ahmed et al. investigated geometrical texture elements such as depth, diameter, depth-to-diameter ratio, shape, and dimple density. They found that aspect ratio was the most important component in enhancing tribological performance [14].

T. Ibatan and colleagues conducted a critical review of surface texturing. They focused on the evolution of surface texture and its impact on tribological performance, such as friction and load-bearing capacity, under various lubrication regimes. Thin-film coatings, they found, increased wear life and decreased friction [15] when used in conjunction with solid lubricants.

According to Ahmad Firdaus Shamsul Baharin et al., laser surface texturing can minimize friction and wear on reciprocating components by as much as 80% [16].

Also, Atulkumar S. Patil et al. carried out a critical review of laser textured ring and liner contact pair, which were exclusively investigated experimentally on a friction testing machine as well as they investigated the said tribological pair for the frictional evaluation and concluded that shape and size of textured dimple plays an important role during the friction analysis of the pair. They found that when the load increased from 80N to 150N, a ring with spherical dimples of diameter 150 µm showed higher frictional resistance than a ring with square dimples of size 150µm [19,20]. Eduardo Tomanik et al. conducted bench tests with the help of diesel engine piston ring and cylinder liner specimens on a reciprocating test rig. Six different liner surface finishes Slide1, Slide 2, UV laser, Laser 1mm, Laser 3mm, and Non-laser region) were used along with the ring and tested at various loads and speeds. They concluded that as the boundary regime approached, nearly all liner surface finishes showed a coefficient of friction of 0.11. As speed increases initially, the smoother surfaces approach the hydrodynamic regime. Also, the 3mm and smooth non-laser surface showed lower friction. They also concluded that the liner wear was not much affected by the surface finish of it, but the smooth surface of the liner caused lower wear of the ring [22].

Wieslaw Grabon et al. studied and compared the tribological behaviour of cylinder liners with and without textures fabricated by the burnishing method on a reciprocating tester. The textures with 13% area density, 5 µm average depths, and 0.15–0.2 mm diameters were fabricated on the liner surface. It was found that the coefficient of friction was reduced with the use of textured liners by the burnishing process compared to plateau-honed liners due to the prominent hydrodynamic oil pocket effect in such cases. During another work, they also studied the effects of the topography of cylinder liner on wear and friction of liner–ring system at temperatures of -20ºC and 80ºC, 30 minutes with a 3mm stroke length. They concluded that liner surface height and frictional resistance change at low temperatures were small compared to higher temperatures [23, 24]. Zhiwei Guo et al. conducted a series of tests on a diesel engine tester to evaluate the tribological characteristics of treated cylinder liner piston ring pairs for marine diesel engines with different grooves and concave textures. Using various texture surfaces and speeds, they analyzed the features of the worn textured surface, oil elements content, and abrasive particles' characteristics. They showed that liner-ring paired with regular concave textures has good wear performance compared to regular grooves and concave groove textures. They concluded that regular concave textures with a depth-to-diameter ratio of 0.1 were the most effective for enhancing lubricating and wear liner-ring pair characteristics [25].

S. C. Vladescu et al. investigated texture effect experimentally with a specially developed test rig simulating ring liner interface working at various lubrication regimes. They showed that the grooves pattern on the ring surface perpendicular to its sliding direction proved effective and reduced the friction by 62%. It was possible due to fluid entrapment in the texture, which reduces the asperity-to-asperity contact. Through another experiment, they concluded that during full film lubrication mode, the oil film thickness was reduced due to textures on the liner, leading to an increase in the shear rate of oil and hence friction up to 12%. While under mixed and boundary modes, textures increase the film thickness causing less asperity to asperity contact and reduced friction. Also, they found that though the film thickness increase is small, about 28%, it significantly impacts friction reduction by up to 41%. They also conducted numerous tests to evaluate the effect of laser-textured pockets on the liner-ring interface. They analyzed the wear and friction behaviour of the pair with a special test apparatus at higher loading conditions. They found that an increase in surface roughness of worn-out specimens tends to enter the pair contact into the boundary and mixed lubrication regime and enhances the reduction by up to 70% compared to non-textured specimens. They also concluded that proper selection of surface texture patterns tends to reduce the friction at the liner ring pair interface and is also responsible for reducing oil consumption [26-29].

Xijun Huo et al. studied the effect of laser surface micro-texture discriminating partition on cylinder liner on fuel, oil consumption, engine emission, and tribological behaviour. They concluded that textured liners with higher micro dimple depth and texture density at the top dead centre and main piston skirt contact positions improve the lubrication performance of the ring-liner system. Also, they found that lower texture density at the bottom dead centre and middle stroke conditions reduced oil consumption [33]. Waldemar Koszela et al. fabricated textures on the cylinder liner surface by plastic deformation with Nikasil coating and diamond-like carbon coating on another cylinder liner before texturing. They compared the engine's performance with the help of textured liner and non-textured liner and ring pair. They found that textured surface liners enhanced the engine's power output by 5.8%, and the best performance was observed with textured and diamond-like carbon-coated liners [30]. Eduardo Tomanik et al. investigated the tribological performance of cylinder liner bore piston ring under mixed lubrication mode with the topographical study of honed grey cast iron and coated mirror-like surfaces. They found that coated bore surfaces generate larger hydrodynamic pressure and smaller asperity contacts than regular gray cast iron surface topographies.

Furthermore, results also showed that fluid pressure generation was basically due to honing grooves compared to pores available on the coated bore surfaces [31]. Roop Lal et al. reviewed the wear and friction nature of the cylinder liner and piston ring interface and concluded that plasma nitrided rings have lower wear rates than those nitrided with gas. In contrast, the frictional performance of the liner ring pair is associated with the plateau nature of the liner [32].

This research aims to study the tribological performance of laser micro-textured piston rings and cylinder liners, miming the ring-liner contact found in a medium-duty passenger car with a gasoline engine. Tribological performance is studied at midstroke operating conditions, which corresponds to a mixed lubrication regime, at a constant speed of 1500 RPM and 0.5m/s of sliding velocity, with spherical and square shape dimpled textured piston rings at 150ºC, which simulates the realistic conditions of an internal combustion engine.

2. Material and Methods

2.1. Specimen Preparation

In order to get these samples, we cut them from commercially available compression piston rings consisting of cast iron and gas-nitrided steel that are utilized in medium-duty passenger gasoline engines. To experiment, piston rings of 20mm in circumference were employed, as well as piston rings of 25mm in circumference and piston rings of 3mm in circumference, all having 1.5mm thickness and 3mm breadth. Wire-cut Electro Discharge Machining (EDM) was used to cut both specimens to the appropriate size.

Samples of piston rings and cylinder liners were tested in NABL-certified laboratories, and their chemical composition, surface roughness, and hardness were summarized as shown in Table 1.

Table 1. Material Properties of Piston ring and Cylinder liner

Specimen	Chemical Composition (%)	Hardness (HV)	Surface Roughness-Ra(µm)	Surface Roughness-Rz (µm)
Piston Ring	Fe-92.57,C-4.03, Mn-0.58, Si-2.52,P-0.24, S-0.053,Cr-0.1	234 HV	0.374	2.550
Cylinder liner	Fe-93.44,C-3.66,Mn-0.49, Si-2.18,P-0.15, S-0.084	234.66 HV	1.960	8.771

As for the piston ring texturing, we used a 90W nanosecond pulsed commercial laser from Marko Laser, Germany, with a frequency of 25 hertz for our surface texturing process. The confocal microscopic images (Olympus OLS-5000 model) of laser textured ring specimens for spherical dimple of size 150µm. 500 µm and square dimples of size 150µm, 300µm, and 500µm, respectively, are shown in Figure 1.

The details of laser textured piston ring geometric parameters like dimple shape, dimple diameter or dimple size, etc., are summarized as shown in Table 2

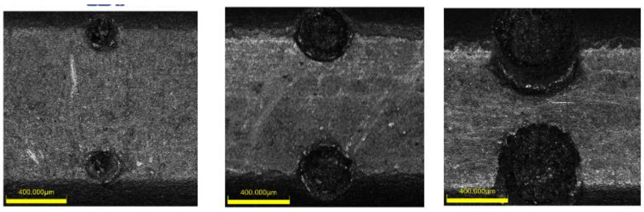


Fig. 1a Confocal microscopic images of the micro-textured piston ring specimens of a spherical dimple of 150µm, 300 µm, and 500µm size

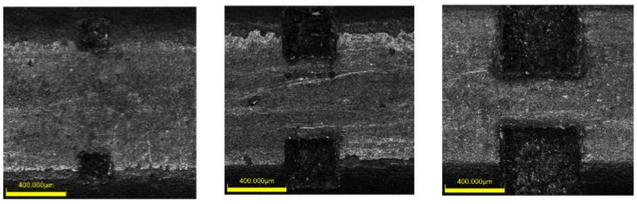


Fig. 1b Confocal microscopic images of the micro-textured piston ring specimens of a square dimple of 150µm, 300 µm, and 500µm size

Table 2. Details of geometric parameters of micro-textured piston ring specimen

Piston Ring Specimen No.	Shape of Dimple	Dimple Diameter/ size (µm)
L1 and L7	Spherical	150
L2 and L8		300
L3 and L9		500
L4 and L10	Square	150
L5 and L11		300
L6 and L12		500
L13and L14	Non-Textured Piston ring specimens	

2.2. Details of Experimental setup

An LRT from Ducm India Ltd., Bangalore, mimics piston ring and cylinder liner sliding action and was used to study friction and wear on the laser surface textured piston rings. A pneumatic circuit applies pressure to the top specimen using a custom upper specimen holder. The friction and normal forces are measured using high-precision lateral and normal force sensors. A data collection system using Win-Ducom software recovers and saves all test data to a computer. Figures 2a and 2b show a schematic diagram and a real image of an experimental setup.

All the experiments were carried out for 12 minutes at 150°C with a particular weight (load), constant speed, and frequency of reciprocation. Averaging the data from the data gathering system was used to analyze all of the tests completed just once.

High-performance semi-synthetic oil SAE 20W40 is utilized as a lubricant during the testing, with a density of 895.4 kg/m^3, a viscosity of 14.5x10-6 m^2/s, and a flash point of 231°C.

The piston ring and cylinder liner can be lubricated in any of the three ways during sliding movements. However, mixed lubrication is more often [8] when doing tribological evaluations of such a pair, keeping the speed constant while also varying the loading conditions because the loading conditions change with time [9]. To simulate nominal contact pressures of 2.5Mpa and 5Mpa at the ring-to-liner tribological pair interface, this experiment applied loads of 80N and 150N. [7]. Tests on the reciprocating friction were carried out at a frequency of 25Hz and a stroke length of 10mm [7]. Twelve minutes was the time limit for all of the experiments. Table 3 lists all of the experimental test parameters utilized in the experiment.

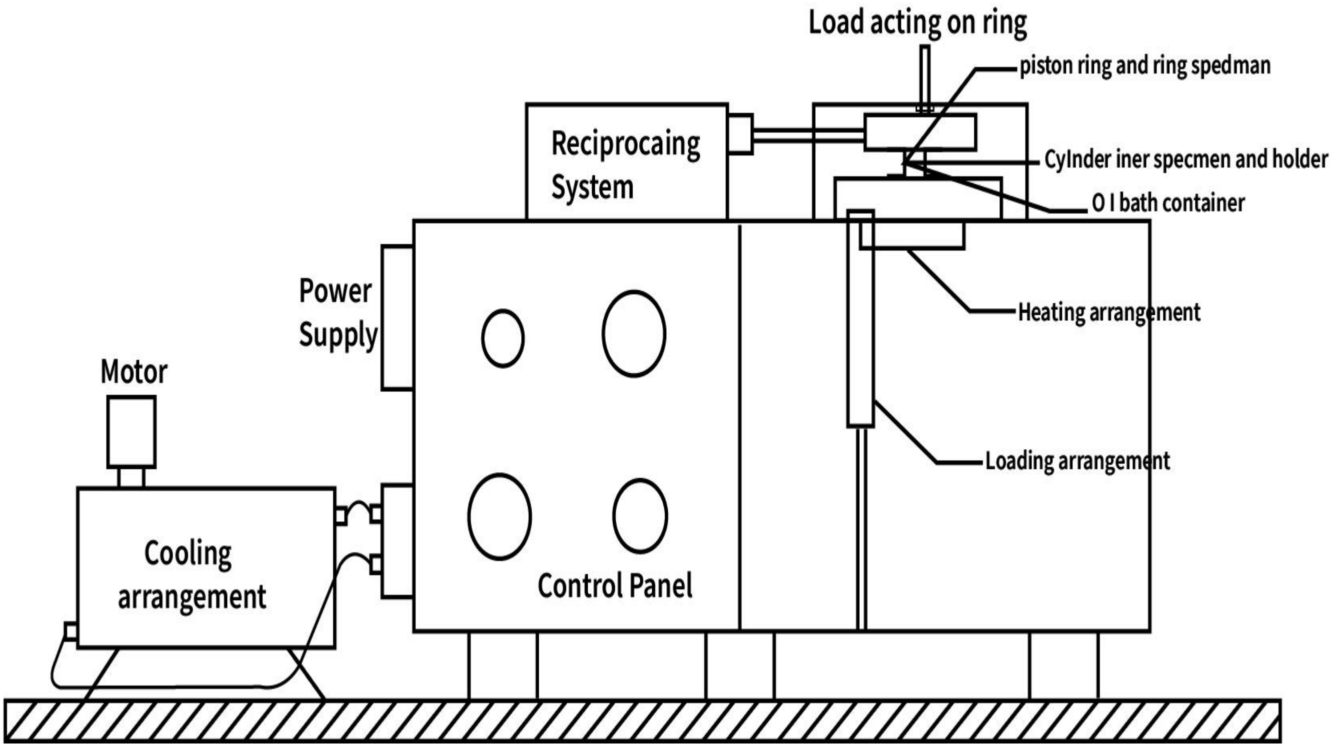


Fig. 2a Schematic diagram of an experimental setup of Linear Reciprocating Tribometer

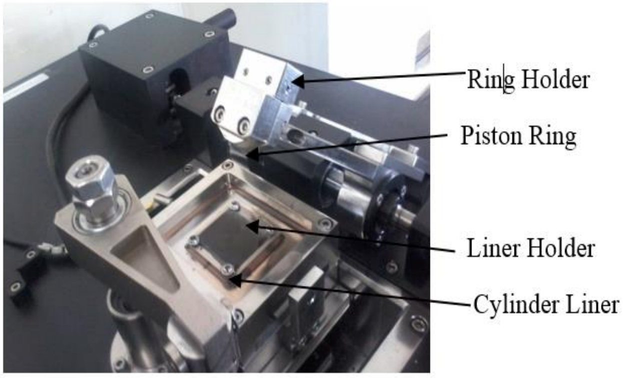


Fig. 2b Experimental setup showing ring and liner samples in Linear Reciprocating Tribometer

Table 3. Experimental parameter details

Parameter	Details of Values
Applied Load	80N and 150N
Speed of Sliding	0.5 m/s
Temperature	150ºC
Oil/Lubricant	SAE 20W40
Length of Stroke	10mm
Reciprocation Frequency	25Hz
Test Duration	12 minutes

2.3. Experimental Procedure

The friction testing of the ring and liner contact was carried out using the ASTM G181-11 standard [9] throughout the experiments. The specimens were both washed and dried with acetone before each test. Both specimens were then secured in the tribometer's bespoke specimen containers. Load, rotational speed, reciprocating frequency, time interval, and experiment length were all used as anticipated. Numerous laser-textured surfaces might be discovered. Combinations were tested over the prescribed amount of time, as stated above.

The output parameters, including friction coefficient, frictional force, and wear in microns, were recorded using the data collection system with Win-Ducom Software. Laser-textured piston rings and cylinder liners were subjected to frictional and wear testing using average values of the above output parameters.

3. Results and Discussions

After all the tests were completed, the data were analyzed to assess the effect of dimple size, shape, and area ratio on the coefficient of friction and wear between the interacting pair under constant speed and changing load circumstances.

Table 4. Details of pair combinations for conducting trials

Trial No.	Ring No. and liner	Load (N)	Trial No.	Ring No. and liner	Load (N)	Area Ratio (%)
1	L1	80	8	L7	150	1
2	L2	80	9	L8	150	5
3	L3	80	10	L9	150	13
4	L4	80	11	L10	150	1.5
5	L5	80	12	L11	150	6
6	L6	80	13	L12	150	17
7	L13	80	14	L14	150	-

The details of specimen pair combinations for conducting trials are given in Table 4.

3.1. Effect of dimple size and shape on the coefficient of friction (COF) of the ring liner interface

Figure 3 and Figure 4 illustrate the coefficient of friction variation for spherical and square-shaped dimple rings at 80N, 1500 rpm, and 150°C, respectively, under these circumstances. It can be revealed from Figure 3 that the ring with spherical dimples of diameter 300µm shows good frictional resistance as compared to non-textured rings and other textured rings. It gives approximately 5.02% enhancement in frictional resistance compared to a non-textured ring. Similarly, Figure 4 indicates that the ring with 300µm square dimples has superior frictional resistance compared to non-textured and other textured rings. Compared to a non-textured ring, it provides a 23.62 percent increase in frictional resistance. The square dimple ring outperformed the spherical dimple ring regarding frictional resistance between interacting pairs.

Spherical and square dimples act as microscopic step bearings because the oil encapsulation provides extra hydrodynamic pressure, increasing the load-carrying capacity, which is difficult in non-textured rings. [7] As a result, the sliding surfaces benefit from creating a lubricating oil film that helps them bear more weight. [13]. Also, as the ring liner interface is operating at mid-stroke operating conditions, the availability of mixed lubrication tends to enhance the frictional resistance of the tribological pair.

Figures 5 and 6 illustrate the same time-dependent friction coefficient fluctuation for loads of 150 N, 1500 rpm, and 150ºC, respectively. Piston rings with 150µm dimples of spherical dimples produce superior frictional resistance than non-textured and other textured rings, as shown in Figure 5. Frictional resistance was found to be increased by 13.79 percent over a non-textured ring. Figure 6 also shows that, as inferred, the ring with 500µm square dimples has greater frictional resistance than non-textured and other textured rings. Compared to a non-textured ring, a 5.80 percent change in frictional resistance was observed. Because the spherical dimple ring increases the frictional resistance of the interacting pair, it has performed better than the square dimple ring.

Increased loading from 80N to 150N shows that dimple form and size significantly impact the frictional behavior of the interacting pair of materials. At low load conditions, a square-shaped dimple ring of 300µm has better frictional resistance; at high load conditions, a spherical-shaped dimple ring of 150µm has better frictional resistance.

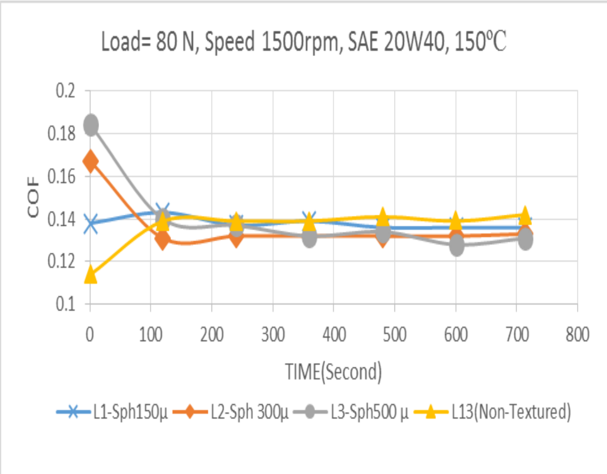


Fig. 3 Coefficient of friction at 80N and 1500 rpm for spherical size dimple piston ring

It is because of an increase in load [17] as well as high sliding velocity plastic deformation of the asperities on the ring and liner interface that occurs, which leads to the formation of smooth surfaces resulting in the reduction of coefficient of friction. But if we observe the case of a square dimple ring, it can be revealed that due to an increase in loading conditions, a slight enhancement in frictional resistance is observed as compared to a spherical dimple ring. Another important point to be noticed is that at higher loading conditions, the spherical dimple-shaped ring is better for its frictional resistance than a square-shaped dimple ring.

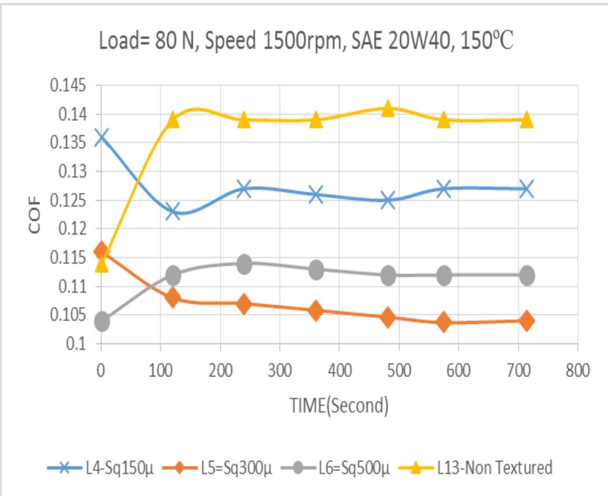


Fig. 4 Coefficient of friction for 80N and 1500 rpm for square size dimple piston ring

Also, there may be a change of regime from mixed due to a hydrodynamic increase in load, which will enhance the load-carrying capacity of the tribological pair. Table 5 shows the percentage variation in the frictional coefficient for a textured ring and liner pair calculated at 1500 rpm with loads of 80N as well as 150N.

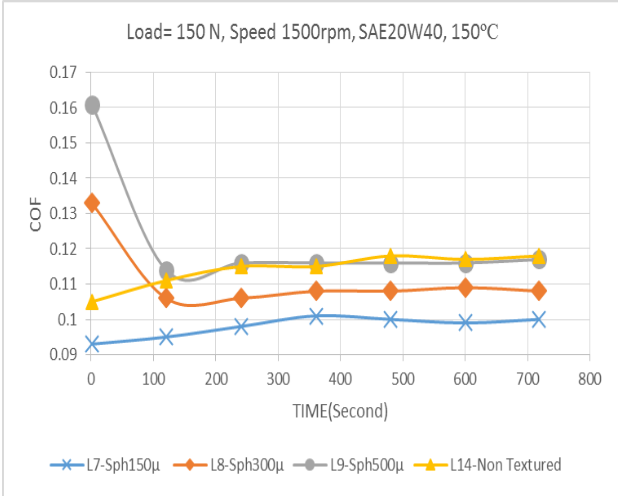


Fig. 5 Coefficient of friction at 150N and1500 rpm for spherical dimple piston ring

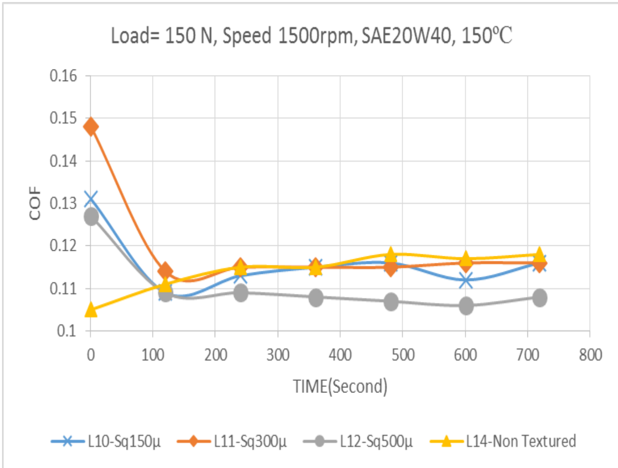


Fig. 6 Coefficient of friction at 150N and 1500 rpm for square dimple piston ring

The temperature considered here is also 150ºC. To gain a fresh perspective on the ring liner system's frictional performance that differs from that addressed in the preceding sections of the paper, these data represent the average coefficients of friction (arithmetic mean values) for each trial.

It can be seen from the tabular data that for a spherical-shaped dimple ring, as the dimple diameter increases, the percentage reduction of coefficient of friction lowers, which shows that the spherical dimples with lower diameter enhance the frictional behaviour of the ring and liner surfaces. On the other hand, for a square shape dimple ring, as the dimple size increases, the percentage reduction of coefficient of friction also lowers, as seen in the spherical dimple case, which shows that the dimples with lower size enhance the frictional behaviour of the ring and liner interface with the increase in loading conditions.

Table 5. Percentage variation in friction coefficient for various ring liner combinations

Dimple Shape	Dimple Size	Average Coefficient of Friction at 80N	Average Coefficient of Friction at 150N	% Variation of COF
Non-Textured	Non-Textured	0.1393	0.1145	Reduction 17.80
Spherical	150µm	0.1387	0.0987	Reduction 28.83
	300µm	0.1323	0.1071	Reduction 19.04
	500µm	0.1341	0.1161	Reduction 13.42
Square	150µm	0.1254	0.1123	Reduction 10.44
	300µm	0.116	0.1148	Reduction 1.03
	500µm	0.112	0.1078	Reduction 3.75

But suppose the comparison of the percentage reduction of spherical and square-shaped dimple rings is done. In that case, it may be noted that the spherical-shaped dimple of 150µm shows good tribological performance compared to other spherical, square-shaped dimple rings and non-textured ring specimens.

There are two reasons for this: first, the reduced coefficient of friction caused by the increased load up to a certain point, and second, the mid-stroke operating conditions. It's possible to have both asperity-to-asperity contacts and lower friction coefficients when enough lubricant is available at the ring liner interface, resulting in a mixed lubrication regime [18]. Also, greater dimple sizes do not have superior frictional resistance than smaller dimple diameters [7, 15]. Due to an enlarged dimple area on the ring's surface, which exhibits higher oil trapping in the dimple zone, there is an oil shortage between the ring and the liner [8]. The increased coefficient of friction is caused by wear particles generated when the asperity of the ring and the asperity of the liner surface come into direct contact.

3.2. Effect of Area Ratio on the Coefficient of Friction of the Ring Liner Interface

The spherical dimple diameter and square dimple sizes used on the surface of piston ring specimens range from 150µm to 500µm which gives various area ratios ranging from 1%, 5%, 13% for spherical dimples and 1.5%, 6%, 17% for square dimple piston ring specimen respectively. When the piston ring specimen has a square dimpled shape, and an area ratio of 6 percent, a reduction in coefficient of friction can be shown in Figure 7. Also, from Figure 8, it has been seen that the reduction in coefficient friction is observed for spherical-shaped dimple piston ring specimen at 150N loading condition and the area ratio of only 1%. The above results reveal that for a moderate area ratio of 6%, the square-shaped dimpled piston ring specimen has shown good frictional behaviour at a low load of 80N.

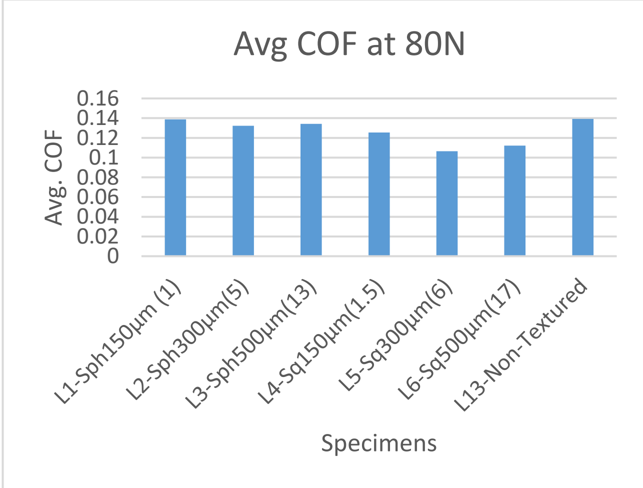


Fig. 7 Average friction coefficient for spherical and square dimple shape at 80N and 1500 rpm

But as the load increases to 150N, the spherical shape dimpled piston ring specimen has shown good tribological behaviour with a low area ratio of 1%.

From the results, it can be revealed that the lower area ratio should be used at high-loading conditions to enhance the frictional behaviour of the ring and liner interface.

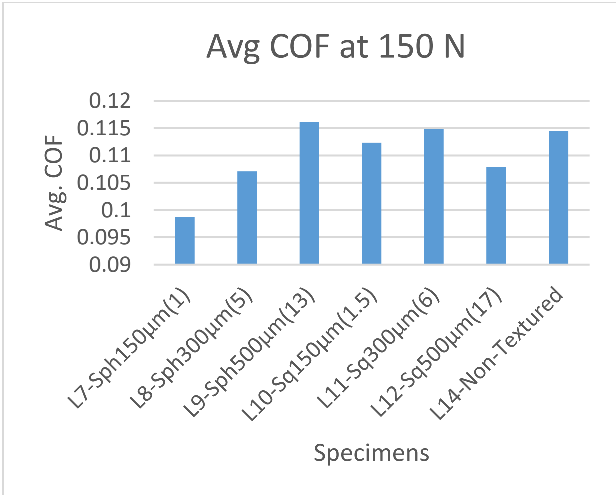


Fig. 8 Average friction coefficient for spherical and square dimple shape at 150N and 1500 rpm

3.3. Effect of dimple size and shape on Wear of Cylinder liner

The material length (in microns) was eliminated from the test surfaces using the data collecting system in simulated tests performed on a linear reciprocating tribometer under loading conditions of 80N and 150N, respectively. The values obtained were plotted against the time for analyzing the tribological pair's wear performance, as shown in Figure 9 to Figure 12.

At 80N load, the cylinder liner wear was found to be lower interacting with non-textured piston ring specimens as compared to spherical dimple piston ring as well as the square dimple piston ring specimens, as shown in Figure 9 and Figure 10. It can be observed that the cylinder liner with non-textured rings has shown wear of 8.93µm while the cylinder liner with spherical (diameter of 150µm) and square (size of 500µm) shaped dimple rings have shown the highest wear of 74.69µm and 264.79µm respectively. It can be revealed from the above data that though the dimples are proving effective for better frictional resistance, they may lead to the wear of the counterpart. This wear depends upon the shape and size of the dimple on the piston ring.

The liner surface has undergone abrasive wear due to the sharp edges available at the periphery of the spherical and square-shaped dimple. Also, the micro burr particle trapped between the ring and liner surface may be responsible for the increase in wear of the liner due to dimple rings [8].

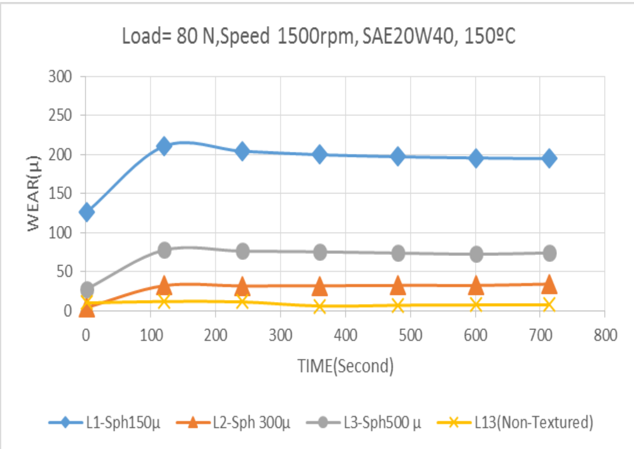


Fig. 9 Wear of liner sliding with spherical dimple shape piston Ring specimen at 80N and 1500 rpm

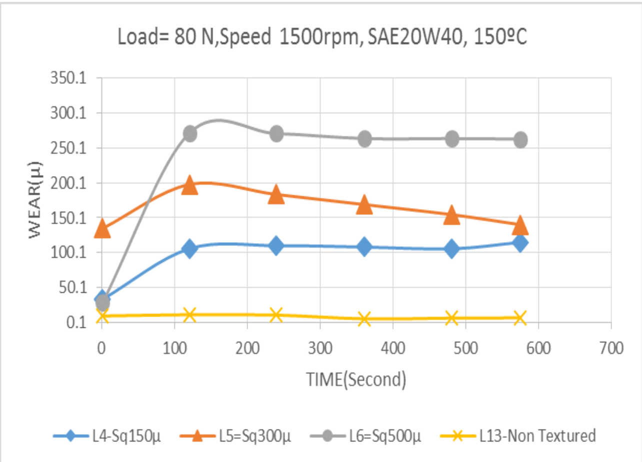


Fig. 10 Wear of liner sliding with square dimple shape piston ring specimen at 80N and 1500 rpm

The spherical dimple ring of 150µm is responsible for lower wear as compared to the square dimple ring of size 500µm because of change in shape and size of the dimple directly affects the stress concentration area of laser machined dimples which in turn is responsible for the wear enhancement [8]. It can be revealed from the above discussions that though the dimples are proving to be effective for better frictional resistance, on the contrary part, it may lead to wear of the counterpart. This wear depends upon the shape and size of the dimple on the piston ring.

At 150N load, the cylinder liner wear was found to be lower while interacting with 300µm spherical as well as square-shaped dimple piston rings are compared to non-textured and higher-sized spherical and square-shaped dimple rings, as shown in Figure 11 and Figure 12. It can be observed that the liner with a 300µm spherical dimple has shown lower wear of 15.09µm and the liner with a 300µm square dimple has shown lower wear of 17.81µm. But the non-textured as well as larger sized spherical (diameter with 500µm) and square (size of 500µm) shaped dimple rings, while interacting with liner, have shown higher wear of 76.10µm, 96.65µm and 104.53µm respectively.

It can be revealed from the above discussions that at higher loading conditions, the dimples on the piston ring are proven effective for the wear reduction of the liner. Due to increased load, the micro burrs responsible for the higher wear at low load conditions may be retained in the ring surface micro pockets, lowering the abrasive wear [8].

Fig. 11 Wear of liner sliding with spherical dimple shape piston ring specimen at 150N and 1500 rpm

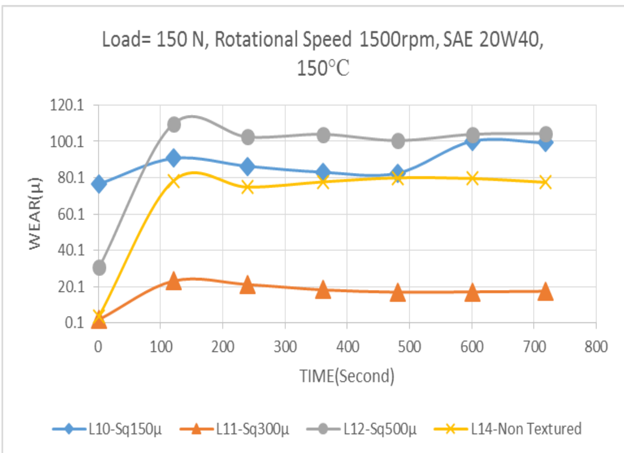


Fig. 12 Wear of liner sliding with square dimple shape piston ring specimen at 150N and 1500 rpm

4. Correlation of obtained results with Surface Morphology of the Specimen

The results shown in the graphs above closely agree with the confocal microscope photographs of the cylinder liner specimen worn-out surfaces. Before and after the tribological test, the cylinder liner specimens' micrographs were analyzed before and after the tribological test to better understand the wear pattern.

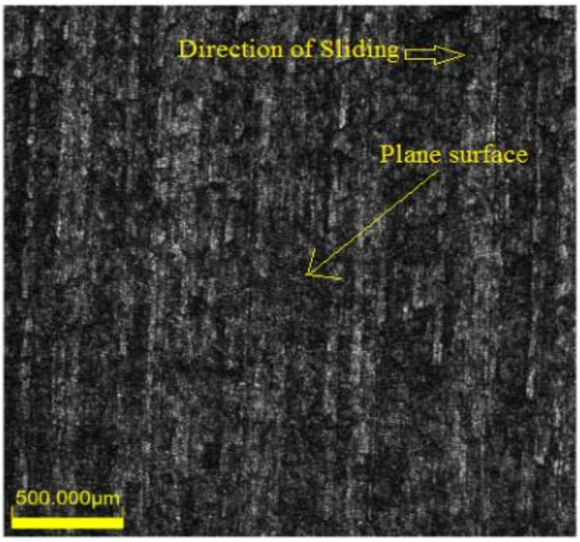
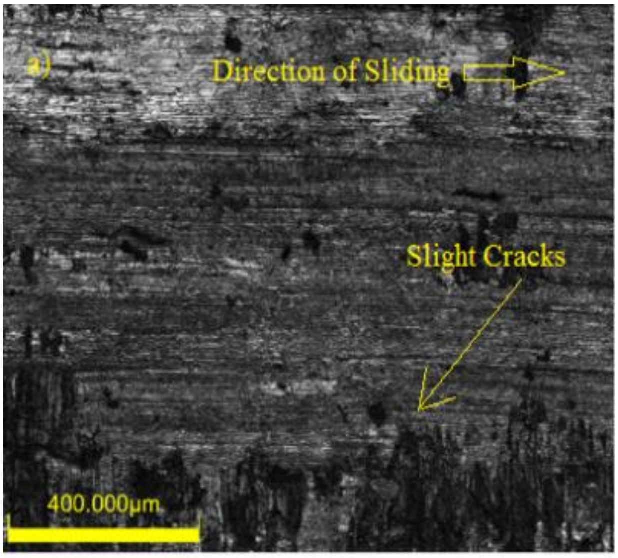
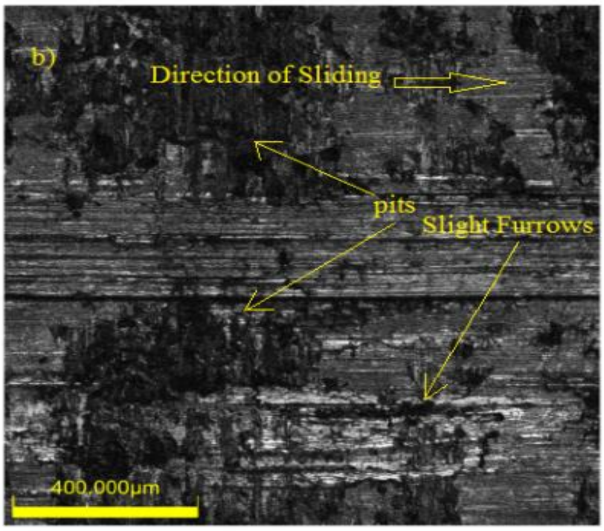


Fig. 13 Cylinder liner before a test

The morphologies of the wear surface of the cylinder liner may be used to study various reasons for the loss of cylinder liner material. The cylinder liner specimens were analyzed with the help of a confocal microscope (Olympus OLS-5000 Model) for wear patterns.

Figure 13 shows the morphology of the cylinder liner specimen before the tribological test, which indicates the plane surface of it without any deterioration of the surface as well as no cracks, pits, or furrows.





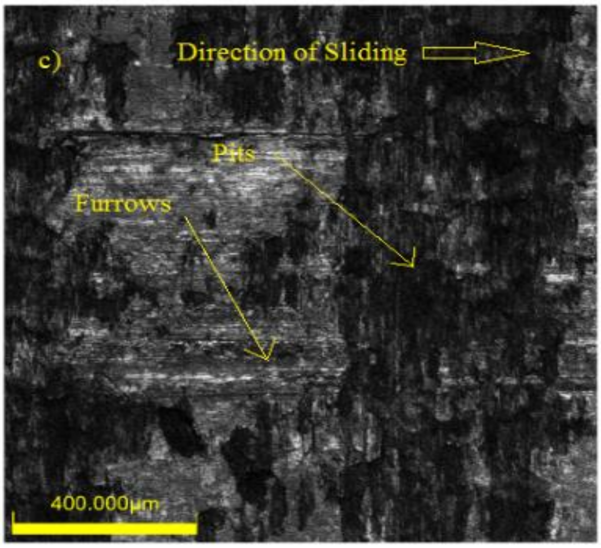
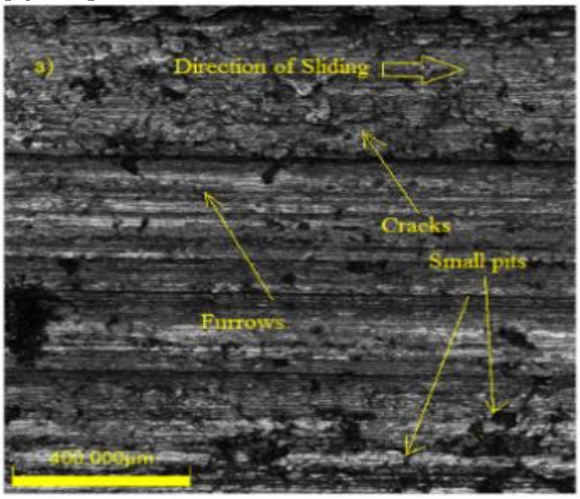


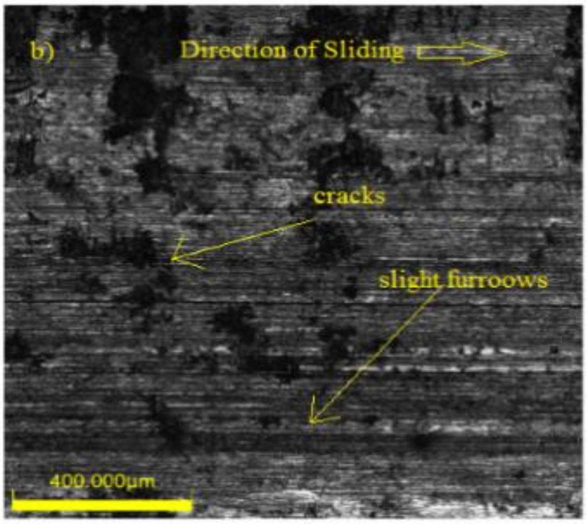
Fig. 14 Cylinder liner micrographs after test with a) non-textured b) spherical 150µm c) square 500µm ring at 80N

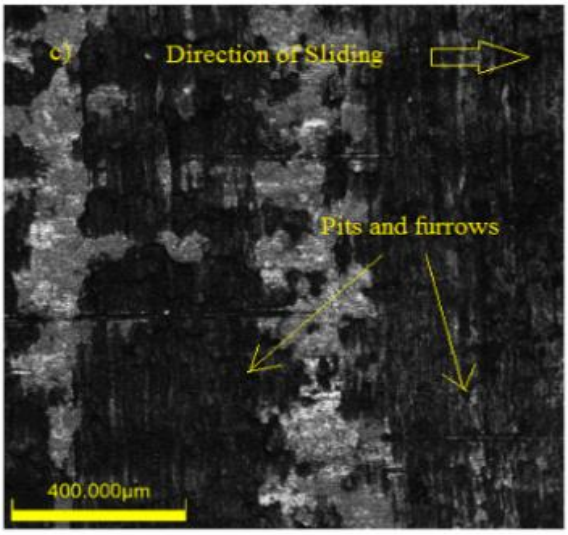
Figure 14a to 14c shows the cylinder liner wear interacting with non-textured, 150µm spherical, and 500µm square-sized dimple ring at 80N load condition. It can be seen from the images that 150µm spherical and 500µm square-sized dimple ring shows maximum wear of liner as compared to non-textured ring specimen. The images clearly show that the small micro-cracks in the sliding direction are observed on the liner surface interacting with the non-textured ring. In contrast, the extra removal of material in the form of slight furrows, pits, and cracks in the sliding wear direction can be observed for the liner surface interacting with the 150µm spherical and 500µm square-sized dimple ring. It can also be revealed from the above micrographs that a 150µm spherical ring has shown lower wear than a 500µm square-sized dimple ring.

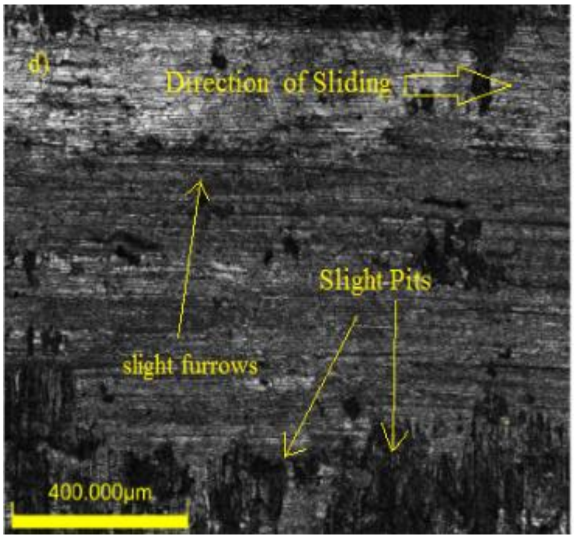
Figure 15a to 15e shows the cylinder liner wear interacting with non-textured, 300µm and 500µm spherical and 300µm and 500µm square sized dimple ring at 150N load condition. From the micrograph images given below, it may be observed that the liner in contact with the 300µm spherical dimple ring shows minimum wear compared to the non-textured ring specimen, but 500µm spherical dimple ring shows the maximum wear of the liner surface. The small pits, slight furrows, and micro-cracks available in the liner surface interacted with the 300µm spherical, implying less wear of the liner surface as compared to the liner in contact with the non-textured ring and 500µm spherical sized dimple ring where large furrows and cracks can be visualized which indicates the higher amount of wear.

Also following micrograph images shows that the liner in contact with the 300µm square-sized dimple ring shows minimum wear compared to the non-textured ring and 500µm square dimple ring. The small pits, slight furrows, and micro-cracks available on the liner surface in contact with the 300µm square dimple ring imply less wear of the liner surface compared to the liner in contact with the non-textured and 500µm square size dimple ring. The big furrows and pits observed on the cylinder liner surface in contact with the 500µm square dimple ring imply a higher amount of liner wear.









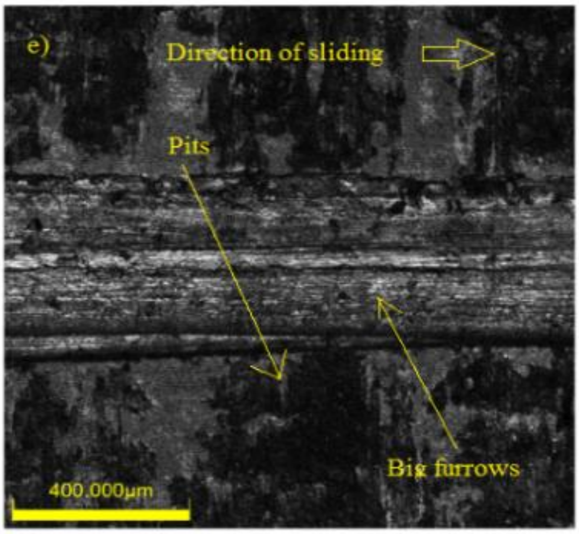


Fig. 15 Cylinder liner micrographs after test with a) non-textured b) spherical 300µm c) spherical 500µm d) square 300µme) square 500µm ring at 150N

5. Conclusion

The tribological performance of laser micro-textured piston rings and cylinder liners is examined under various operating conditions.

It has been found that,

- Dimples on piston rings and regular cylinder liners significantly impact their frictional performance.
- At varying loading conditions of 80N and 150N, the 150µm dimple piston rings show good frictional resistance with a reduction of coefficient of friction up to 28.83% and 10.44%, respectively, irrespective of the shape of the dimple.
- Spherical textured rings are more resistant to piston-ring sliding than squared-shaped textured rings in terms of friction (PRCL).
- Analysis of the frictional behavior of PRCL contacts also relies heavily on the area ratio, and at high loading conditions, the lower area ratio should be used to enhance the frictional behaviour of the ring and liner interface
- The wear rate of the cylinder liner is concerned; the 300 µm spherical textured piston ring specimen shows incredibly low.
- The wear resistance of non-textured piston rings is better at low load conditions, but as the load increases, the spherical or square-shaped dimpled ring has shown a reduction in wear. Specifically, the spherical dimple ring of 300µm shows good wear resistance.

Future Work

Optimizing the texture parameters like dimple shape and dimple density for micro-textured piston ring-cylinder liner interface can be evaluated to minimize friction of this interacting pair.

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References

[1] Ezhilmaran, N.J. Vasa, L. Vijayaraghavan, “Investigation on Generation of Laser Assisted Dimples on Piston Ring Surface and Influence of Dimple Parameters on Friction,” *Surface & Coatings Technology,* vol. 33, pp. 314-336, 2018.

[2] G. Ryk, Y. Kligerman, I. Etsion, “Experimental Investigation of Laser Surface Texturing for Reciprocating Automotive Components,” *Tribology Transactions,* vol. 45, no. 4, pp. 444-449, 2022.

[3] G. Ryk, Y. Kligerman, I. Etsion, A. Shinkarenko, “Experimental Investigation of Partial Laser Surface Texturing for Piston Ring Friction Reduction,” *Tribology Transactions,* vol. 48, pp. 593-588, 2005.

[4] G. Ryk, I. Etsion, “Testing Piston Rings with Partial Laser Surface Texturing for Friction Reduction,” *Wear,* vol. 261, pp. 792-796, 2006.

[5] Nathan W. Bolander and Farshid Sadeghi, “Surface Modification for Piston Ring and Liner,” *IUTAM Symposium on Elasto-Hydrodynamic and Micro Elasto-Hydrodynamics*, pp. 271-283, 2006.

[6] I. Etsion and E. Sher, “Improving Fuel Efficiency with Laser Surface Textured Piston Rings,” *Tribology International,* vol. 42, pp. 542-547, 2009.

[7] Cong Shen and M. M. Khonsari, “The Effect of Laser Machined Pockets on the Lubrication of Piston Ring Prototypes,” *Tribology International,* vol. 101, pp. 273-283, 2016.

[8] Yali Zhang, Xiaogang Zhang, Tonghai Wu and You-bai Xie, “Effects of Surface Texturing on the Tribological Behavior of Piston Rings Under Lubricated Conditions,” *Industrial Lubrication and Tribology,* vol. 68, no. 2, pp. 158-169, 2016.

[9] ASTM G181-11 Standard, “Standard Test Method for Conducting Friction Tests of Piston Ring and Cylinder Liner Materials Under Lubricated Conditions,” *Standard Products*, 2011

[10] Wei Haijun, "Study on the Tribology of the Cylinder and Piston Ring of the Vehicle Diesel with Surface Roughness and Lubrication Oil," *IEEE Third International Conference on Measuring Technology and Mechatronics Automation,* pp. 589-592, 2011.

[11] Parul Mishra and P. Ramkumar, "Effect of Micro Texture on Tribological Performance of Piston Ring-Cylinder Liner System Under Different Lubrication Regimes," *SAE International,* vol. 28, pp. 0052, 2018.

[12] Parul Mishra & P. Ramkumar, "Effect of additives on a Surface Textured Piston Ring–Cylinder Liner System," *Tribology - Materials, Surfaces & Interfaces,* vol. 1, no. 10, pp. 67-75, 2019.

[13] Vladescu S.C, Olver A.V, Pegg I.G, and Reddyhoff T, "The Effects of Surface Texture in Reciprocating Contacts - An Experimental Study," *Tribology International,* vol. 82, pp. 28-42, 2015.

[14] Arslan Ahmed et al., "An Overview of Geometrical Parameters of Surface Texturing for Piston/Cylinder Assembly and Mechanical Seals," *Meccanica,* vol. 51, pp. 9-23, 2015.

[15] T. Ibatan et al., "Recent Development on Surface Texturing in Enhancing Tribological Performance of Bearing Sliders," *Surface & Coatings Technology,* vol. 272, pp. 102-120, 2015.

[16] Ahmad Firdaus Shamsul Baharin et al., "Laser Surface Texturing and its Contribution to Friction and Wear Reduction: A Brief Review," *Industrial Lubrication and Tribology,* vol. 68, pp. 57-66, 2016.

[17] H. K. Trivedi and D. V. Bhatt, "Effect of Lubricants on the Friction of Cylinder Liner and Piston Ring Materials in a Reciprocating Bench Test," *FME Transactions,* vol. 47, no. 1, pp. 23-28, 2018.

[18] V. Ezhilmaran et al., "Investigation of Nd3+: YAG Laser Aided Surface Texturing to Improve Tribological Characteristics of Piston Ring," *Journal of Laser Micro-Nano Engineering,* vol. 12, no. 3, pp. 195-202, 2017.

[19] Atulkumar S. Patil et al., "Effect of Laser Textured Dimples on Tribological Behavior of Piston Ringand Cylinder Liner Contact at Varying Load," *Materials today Proceedings,* vol. 44, pp. 1005-1020, 2021.

[20] Atulkumar S. Patil et al., "A Review of Experimental Tribological Investigations of Piston Ring with Laser Surface Textured Dimples," *An International Conference on Tribology,* TRIBOINDIA 2018, VJTI, Mumbai, SSRN Journal, pp. 1-6, 2018.

[21] V. Ezhilmaran et al., "Femtosecond Pulsed Ti: Sapphire Laser Assisted Surface Texturing on Piston Ring and its Tribology Characterization," *ASME Journal of Tribology,* vol. 143, pp. 041801-1-041801-7, 2021.

[22] Eduardo Tomanik, "Friction and Wear Bench Tests of Different Engine Liner Surface Finishes," *Tribology International,* vol. 41, pp. 1032-1038, 2008.

[23] WieslawGrabon, WaldemarKoszela, "Improving Tribologicalbehaviour of Piston Ring–Cylinder Liner Frictional Pair by Liner Surface Texturing," *Tribology International,* vol. 61, pp. 102-108, 2013.

[24] WieslawGrabon, PawelPawlus, "Effects of Cylinder Liner Surface Topography on Friction and Wear of Liner-Ring System at Low Temperature," *Tribology International,* vol. 121, pp. 148-160, 2018.

[25] ZhiweiGuo, Chengqing Yuan, "Study on Influence of Cylinder Liner Surface Texture on Lubrication Performance for Cylinder Liner–Piston Ring Components," *Tribology Letters*, vol. 51, pp. 9-23, 2013.

[26] Sorin Christian Vladescu, Simon Medina "Lubricant Film Thickness and Friction Force Measurements in a Laser Surface Textured Reciprocating Line Contact Simulating the Piston Ring–Liner Pairing," *Tribology International,* vol. 98, pp. 317-329, 2016.

[27] Sorin Cristian Vladescu, Andrew V. Olver, "Combined Friction and Wear Reduction in a Reciprocating Contact Through Laser Surface Texturing," *Tribology International,* vol. 358-359, pp. 51-61, 2016.

[28] SorinCristianVladescu, AlessendraCiniero, "Looking into a Laser Textured Piston Ring-Liner Contact," *Tribology International,* vol. 115, pp. 140-153, 2017.

[29] Tran Minh Duc, Tran The Long, "Effects of MQL and MQCL Parameters on Surface Roughness in Hard Milling of SKD 11 Tool Steel," *SSRG International Journal of Mechanical Engineering*, vol. 7, no. 10, pp. 28-31, 2020.
Crossref, https://doi.org/10.14445/23488360/IJME-V7I10P106.

[30] WaldemarKoszela, PawelPawlus, "The Combined Effect of Surface Texturing and DLC Coating on the Functional Properties of Internal Combustion Engines," *Tribology International,* vol. 120, pp. 470-477, 2018.

[31] Eduardo Tomanik, Mohamed El. Mansori, "Effect of Waviness and Roughness on Cylinder Liner Friction," *Tribology International,* vol. 120, pp. 547-555, 2018.

[32] Roop Lal, R. C. Singh, Ranganath M. S. and S. Maji, "Friction and Wear of Tribo-Elements in Power Producing Units for I. C. Engines- A Review," *International Journal of Engineering Trends and Technology,* vol. 14, no. 5, pp. 225-231, 2014.

[33] XijunHuo, Jianguo Sun, "Research on Discriminating Partition Laser Surface Micro-Texturing Technology of Engine Cylinder," *Tribology International,* vol. 98, pp. 190-196, 2016.