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# A review of experimental tribological investigations of piston ring with laser surface textured dimples

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**ABSTRACT**

In an automobile internal combustion engine plays a vital role but the efficiencies like thermal and mechanical efficiency of an internal combustion engine is relatively low. It is due to dissipation of large part of its fuel energy in the form of heat loss and loss for overcoming the friction. The friction between the piston ring and cylinder liner pair, rotating engine bearings, valve train etc. is responsible for the power loss in an engine. The attempts to reduce the friction between these interacting surfaces leads to the advantages like reduction in consumption of fuel, high power output, reduction in consumption of oil, reduction in exhaust emissions etc. The reduction of friction as well as wear can be achieved by the proper lubrication and proper surface treatment of the interacting components. The surface modification technique like laser surface texturing (LST) is mostly used for improving the tribological performance of interacting surfaces. Therefore the effect of laser surface textured dimples especially on piston ring surface to evaluate the performance of piston ring and cylinder liner tribological pair should be studied properly. Most of the researches carried out the theoretical study about this but very few have carried out the experimental investigations about the tribological evaluation of ring and liner pair. In this research work the review of the experimental work done for tribological investigation of piston ring with laser surface textured dimples on outer surface of ring and cylinder liner interface by various researchers was carried out. The review work in this paper describes the effect of various dimple parameters like shape, size and depth of dimple, area ratio load, speed etc. on the tribological performance of the ring and liner interface.

Keywords- *Laser Surface Texturing (LST), dimple geometry, friction, wear*

## 1. Introduction:

The internal combustion engine plays a vital role in all the automobiles but the thermal efficiency and mechanical efficiency of internal combustion engine is relatively low as large part of its fuel energy is dissipated in the form of heat loss and frictional loss. By improving the tribological performance of internal combustion engine that means by reducing the friction as well as in turn wear between the interacting surfaces like piston ring and cylinder liner pair, rotating engine bearings, valve train etc. the advantages like reduction in consumption of fuel, high power output, reduction in consumption of oil, reduction in exhaust emissions harmful to human beings. The reduction of friction as well wear can be achieved by the proper lubrication and proper surface treatment of the interacting components. The surface treatment in the form of surface coating or surface modification of piston ring or cylinder liner component material are the probable options with which there may be reasonable amount of reduction in friction as well as wear of the interacting surfaces. Amongst the various components of internal combustion engine piston ring is the most crucial tribological component since it is undergoing rapid variations of load, different speed ranges, variation of temperature and the availability of lubricant film. In one single stroke of the piston the ring may be exposed to all the three modes of lubrication like boundary, mixed and full fluid film lubrication. In an automobile major share for the total power loss is taken by the upper compression ring and cylinder liner friction therefore the study of piston ring material and reducing the friction and wear of piston ring cylinder liner interface with the help of surface modification of piston ring is of utmost important and needs to be considered in the research work most significantly. In this paper the review of the experimental work done for tribological investigation of piston ring with laser surface textured dimples on outer surface of ring and cylinder liner interface by various researchers was carried out. The review work in this paper describes the effect of various dimple parameters like shape, size and depth of dimple, area ratio load, speed etc. on the tribological performance of the ring and liner interface.

Most of the researchers have carried out the tribological investigations of piston ring and cylinder liner tribological pair with the simulated conditions by scaling down the parameters involved in the experiments. Many of them have used the various surface modification processes like burnishing, etching, and mechanical rolling, laser surface texturing etc. but as we need to discuss about the laser textured dimples and its tribological performance which is reviewed in this work.

It may be noted that up to 25% reduction in the friction between ring and liner interface is possible by the surface modification of piston ring surface. In this the speed of the tribological test rig is restricted to some value while conducting the experiments [3]. Also the use of laser surface texturing on piston rings was responsible for the 4% reduction of fuel consumption of engine in actual tribological engine testing done by I. Etsion and E. Sher [5]. Therefore the experimental study of surface modification of piston ring surface for reducing the friction and wear of a piston ring cylinder liner tribological pair is of utmost important and needs to be reviewed for understanding the effect of surface texturing on the tribological behaviour of the piston ring and cylinder liner pair. **G. Ryk et al.** has carried out an experiment to study the effect of micro-surface structure on piston ring which was produced by laser surface texturing. During this experimental study they had observed that friction reduction of up to 40% and 30% was found in first and second configuration of piston rings respectively. They concluded that if the dimple depth is optimum and viscosity of the lubricant is low then the surface texturing gives good results for all the range of flow rates [1]. **G. Ryk et al.** experimentally evaluated the effect of laser surface textured dimples carried out partially on piston ring surface on the frictional behaviour of piston rings. They found that if the speed of test rig is kept within certain limit then up to 25% friction reduction can be obtained with partial laser surface texturing compared to full laser surface texturing. So overall additional 40% improvement in friction reduction over the reduction of friction obtained with the full laser surface texturing compared to the un-textured case is observed [2]. **Nathan Bolander et al.** have investigated experimentally various surface patterns and features to find the potential of it in terms of reduction of friction at the piston ring cylinder liner interface. Their results indicate that laser surface textured piston rings shows high potential to enhance the tribological performance of piston ring cylinder liner interface with reduction in friction level. However they instructed that some more experiments should be carried out to confirm the effect of it obtained in their study. They had shown that the depth of dimple is an important factor which plays a major role in the contact behaviour and needs to be investigated in a proper manner in future investigations [4]. **I. Etsion and E. Sher** had conducted an experiment to evaluate the effect of laser surface textured top piston rings on fuel consumption and exhaust gas composition of an internal combustion engine. During their experimentation they had carried out dynamometer tests at various speed with a Ford transit naturally aspirated 2500 $cm^3$ engine under near half load conditions. They found that laser surface texturing on top piston rings shows reduction in the fuel consumption of the engine but there is no significant change in exhaust gas composition as far as exhaust gas analysis was considered [5]. **Cong Shen and M. M. Khonsari** has carried out some experiments to investigate the effect of pockets with different geometrical shapes on the tribological behaviour of Piston Ring Cylinder Liner (PRCL) contact. In their results they found that the pocket area ratio and dimple depth are the two factors influences severely on the tribological behaviour of piston ring and cylinder liner interface. But the effect of the pocket shape according to them is very negligible. As per their results the pockets with optimum size (Area Ratio=25%, depth=5µm) can have significant effect in terms of friction reduction of Piston Ring Cylinder Liner (PRCL) contact. On the other hand pockets having large area ratio or depth shows very less reduction in friction [6]. **Yali Zang et al.** has investigated the effect of laser surface textured rectangular and circular shaped texture patterns on the piston ring surface against non-textured cylinder liner surface. They found that both the type of surface texture patterns significantly reduces the friction coefficient under lubricated conditions. Also they concluded that rectangular shaped texture pattern has lowest average coefficient of friction among all the textures at the running in conditions [7]. **V. Ezhilmaran et al. (2017)** investigated the textured piston ring samples for their tribological characteristics with different dimples size ranging from 40µm to 130µm, different aspect ratio ranging 0.1 to 0.3 and different area density ranging from 5% to 38% experimentally by using reciprocating tribometer. Their results showed that 16% area density showed lower friction as compared to other combinations of all the dimple diameters considered for the experimentation purpose. The wear of cylinder liner was found to be reduced by 72% during the testing with the piston ring sample with texturing on it having desired dimension as compared with the non-textured ring [8].

So with the available experimental data from above literature survey overview of the same can be summarized as follows.

## 2. Surface texture parameters involved in piston ring and cylinder liner tribological pair:

As per the literature survey in all the experimental work related to tribological evaluation of piston ring and cylinder liner pair the fabrication of surface texture on piston ring was carried out with the help of laser surface texturing method only. As the piston ring specimen surface is reasonably small in dimensions the surface textures created on such specimens should be very small in size and which can be only achieved by the laser surface texturing method. Also with the help of laser surface texturing method the accuracy in dimple shapes and dimple dimensions can be achieved in a proper manner. Therefore researchers have fabricated the surface textures on the piston ring specimens with Laser Surface Texturing (LST) method only. In LST texture dimensions are controlled by various parameters like wavelength of laser beam, pulse duration of laser beam and power of the laser source. Higher power and longer wavelength lead to gradually increase of texture dimensions like diameter, length, width and depth. The material is removed from the surface to be modified is due to melting and vaporization of the material on which the laser surface texturing process is carried out [10]. Pulse duration in laser machines varies and generally depends upon the source media which creates the beam. Generally the most commonly used pulsed solid state lasers for creating the laser surface textures on the metal surfaces like steel, iron, titanium, nickel, cast iron etc. are Nd-Yag laser machines, Niobium or femtosecond laser machines. The diameter of dimple, depth of dimple, length of dimple, width of dimple etc. can be accurately textured by maintaining the wavelength, pulse duration and power of the laser. The same surface textures parameters can be easily engraved with the required dimensions on the material specimens.

The dimensional details like dimple diameter, dimple depth, dimple length, dimple width etc. can be easily measured with the inbuilt facility available in laser machine. It can also be measured from stylus method of surface topography, optical methods like white light interferometry and confocal microscopes etc. which are the most used techniques for the surface topography. Also scanning probe microscopes like atomic force microscopy (AFM) can also be used for measurement of very smooth surfaces [9].

The details of surface texture parameters related to piston ring specimens with reference to the detailed literature survey done can be summarized as given in Table 1. The details of surface texturing parameters like surface textures geometrical shapes like circular, square, rectangular, semielliptical etc., surface texture dimensions like dimple diameter; dimple depth in case of circular shape, length; width and depth in case of square and rectangular shape [1-9]. The density of dimples or the dimple area ratio on the specimen to be tested is also playing an important role in the analysis of tribological properties of the piston ring and cylinder liner surface which is also tabulated in the Table 1.

**Table 1- Summary of surface texture parameters during experimental work by various researchers [3-10]**

| Name of Researchers | Texture Shape | Dimple Diameter (µm) | Dimple Depth (µm) | Aspect Ratio: (Dimple Depth/ Dimple Diameter) | Area Ratio or Dimple Density (%) |
|---|---|---|---|---|---|
| G. Ryk et al. | Spherical-Full | 100 | 10 | 0.1 | 13%/20% |
| G. Ryk et al. | Spherical-Full | 78 | 9 | 0.1 | 10% |
| | Spherical-Partial | 75 | 7 | 0.09=0.1 | 50% |
| G Ryk et al. | Spherical-Partial | 72 | 7.5 | 0.1 | 50% |
| N. W. Bolander et. al. | Circular-Full | 75 to 150 | 1.5 to 11 | - | --- |
| I. Etsion et al. | Spherical/Circular-partial | 90 to 100 | 9 to 10 | 0.1 | 53% to 66% |
| Cong Shen et al. | Square | Length 0 to 1.5 mm, width 0 to 1 mm | 0 to 25.6 | - | 0 to 37.5 % |
| | Semi-ellipse | 1.27mm to 0.50 mm | 5.2 | - | 25% |
| | Trapezoid | 1mm, 0.60 mm and 1.25 mm height | 5.2 | - | 25% |

| | | | | | |
|---|---|---|---|---|---|
| Yali Zang et al. | Circular | 60 | 12 | 0.2 | 15% |
| | Rectangular | Length110 and width 20 | 4 and 9 | - | 10% to 25% |
| V. Ezhilmaran et al./Surface and Coatings Technology/ 2017 | Spherical | 40 ,<br>80 ,<br>130 | 12,<br>25,<br>40 | 0.3 | 5%<br>16%,<br>27%<br>38% |

From the above data it may be observed that the range of surface texture parameters used during the experimentation like dimple diameter varies from 40µm to 150µm, the dimple depth varies from 1.5µm to 40µm, the aspect ratio varies from 0.1 to 0.3 and the area ratio varies from 10% to 38%. Aspect ratio is the ratio of dimple depth to dimple diameter. The data in the Table 1 shows that the aspect ratio approximately varies from 0.1 to 0.3 but more often the aspect ratio value of 0.1 is generally considered by the various researchers while carrying out the experimentation work. Also it can be seen that use of circular/spherical geometrical shape of dimple is more prominent than the other shape of dimple.

Also various important experimental parameters considered during the conduction of the piston ring and cylinder liner tribological simulated experiments are summarized as shown in Table 2. It can be observed that the rotational speed used during the trials varies from 15rpm to 220 rpm, as the tests are of reciprocating type the stroke length varies from 10mm to 100mm, the contact pressure between the interacting surfaces varies from 0.1 Mpa to 0.5 Mpa while the load acting on the ring surface varies from 10N to 130N. Also the lubricating oil used for lubrication purpose ranges from Ultra 40, SAE 20, SAE30 and synthetic oil SAE 20W40. The temperature conditions during the tribological trials were generally of room temperature type at 20ºC to 25ºC and may raise up to 60ºC to 70ºC. One of the simulated conditioned test was carried out at 180ºC temperature which was a high temperature condition as compared to the other tests. Only one test was of actual trial on an internal combustion engine which was at real engine temperature conditions. All the test were conducted on the specially made reciprocating type of tribometer or the readily available tribometers in the laboratories. Other parameters like surface roughness, hardness of ring and liner specimen materials and duration of test were not considered here during the review.

**Table 2 - Summary of Experimental parameters during experimental work by various researchers [3-10]**

| | Experimental Parameter | G. Ryk et al. ,Tribology Transactions/ 2002 | G. Ryk et al. /Tribology Transactions/ 2005 | G. Ryk and I. Etsion/ Wear/2006 | N. W. Bolander/ IUTAM Symposium/ 2006 | Etsion and E. Sher /Tribology International/ 2009 | Cong Shen and M. M. Khonsari/ Tribology International/ 2016 | Yali Zang et al./Industrial Lubrication and Tribology/2016 | V. Ezhilmaran, et al./Surface and Coatings Technology/ 2017 |
|---|---|---|---|---|---|---|---|---|---|
| 1 | Rotational speed | 500-1300 rpm | 500-1200 rpm | 500-1200 rpm | 15 rpm | 1500 to 2200 rpm | 0- 240 rpm | 100-500 rpm | 600 rpm |
| 2 | Stroke length | 100mm | 100 mm | 100 mm | - | - | 25mm | | 10 mm |
| 3 | Load | - | - | - | 16kgf | - | 40N to 80N | 1,2,3,4,5 N | 10 N, 50N, 90N and 130 N |
| 4 | Contact pressure between surfaces | 0.1-0.3 Mpa | 0.1-0.5Mpa | 0.1-0.3 Mpa | - | - | 0.25 Mpa to 0.5 Mpa | - | - |
| 5 | Lubricating oil | Ultra 40 engine oil equivalent to SAE 40 V.I.=95 | Ultra 40 engine oil with V.I.=95 | SAE40 engine oil | SAE 30 | - | SAE 20 oil with dynamic viscosity 0.06 pa. s | SL10W-30 | 20W40 Synthetic oil |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 6 | Temperature | 65 ºc -70ºc | 63 ºc -65ºc | 65 ºc -70ºc | Not given | Actual running condition | At Room Temperature 25ºc | 20ºc | 180°C |
| 7 | Tribometer details | Specially made Reciprocating test rig | Specially made Reciprocating test rig | Specially made Reciprocatin g test rig | Specially made Reciprocatin g test rig | Actual testing with 2500 CC engine | Tribometer CETR UMT-3 | Pin on Disc Tribometer | Reciprocating Friction Tribometer |

## 3. Effect of dimple diameter/size on performance of Piston ring and cylinder liner tribological pair:

The dimple diameter/size has not any significant effect on the frictional performance of piston ring and cylinder liner tribological pair. As the dimple diameters used during the experimentation were ranging from 40µm to 150µm for the different operating conditions and amongst which the 80µm dimple is showing good tribological performance by reducing the friction coefficient. The friction coefficient attained a stable value with the increase in a parameter like dimple size beyond 80µm up to 130µm for the specific operating conditions considered by Ezhilmaran et al. [8].

## 4. Effect of dimple shape on performance of Piston ring and cylinder liner tribological pair:

The dimple shape has a moderate effect on the frictional behaviour of piston ring and cylinder liner tribological pair. As in above cases the circular and rectangular dimple shapes are majorly used by the researchers during the experimentation. In this rectangular shaped dimples has shown 24.1% friction reduction and circular shaped dimples shown nearly 19.7% friction reduction as compared to non-textured ring [6]. It can be seen that the other dimple shapes like semi ellipse and trapezoidal have given higher reduction in friction coefficient as compared to square shaped dimple [7].

## 5. Effect of dimple depth on performance of Piston ring and cylinder liner tribological pair:

The dimples depth is playing a vital role in the tribological investigation of piston ring and cylinder liner tribological pair. The deep dimples cause harmful effects in case of friction and wear of interacting surfaces. G. Ryk et al. [2] varied the dimple depth from 9 to 20 µm under starvation condition and found that dimples of 20 µm depth has increased friction coefficient compared to non-textured specimens.

The dimple depth effect on the performance of piston rings was also studied by Bolander et al. [4] and they concluded that in mixed lubrication regime dimple depths of 1µm and 10µm were used, while experimentation. The results showed that near bottom dead centre with 10µm dimple there is increase in contact of interacting surfaces as compared to 1µm dimple. It shows that low depth dimples has given better performance than the deep depth dimples [4]. As the dimple depths used during the experimentation were ranging from 1.5µm to 40µm for the different operating conditions and amongst which the 25µm dimple depth is showing good tribological performance by reducing the friction coefficient. The friction coefficient attained a stable value with the increase in a parameter like dimple depth beyond 25µm up to 40µm for the specific operating conditions considered by Ezhilmaran et al. [8]. Cong Shen et al. used the rectangular dimples with dimple depth varying from 5.3µm to 25.6µm and found that 5.3µm depth dimples has shown lower coefficient of friction than the dimple having depth of 25.6µm. This shows that deep dimples are not useful in improving the frictional characteristics of the ring and liner contact [6].

## 6. Effect of aspect ratio on performance of Piston ring and cylinder liner tribological pair:

Aspect ratio is the most important parameter for improving the tribological performance of piston ring and cylinder liner system. Ezhilmaran at el. shown that the aspect ratio associated with the minimum friction decreases from 0.3 to 0.2 by increasing the value of dimple diameter from 40µm to 130µm during his experimentation on friction characteristics evaluation of piston ring and cylinder liner pair [8 ].

## 7. Effect of area ratio/dimple density on performance of Piston ring and cylinder liner tribological pair:

The area ratio/dimple density is another important parameter to be influencing the tribological performance of interacting surfaces. Dimple density can be defined as the number of dimples per unit area. Yali Zhang et al. concluded that the 15 % area density is the optimal value which gives lower average friction coefficient as compared to the other 10%, 20% and 25% area densities selected for tribological trails [7]. Cong Shen et al. investigated that the 25% area density has given better performance in terms of friction reduction as compared to the other area densities under study like 12.5% and 37.5% during the tribological evaluation of piston ring and cylinder liner pair [6]. The 16% area density is proved to be beneficial in minimizing friction for all the dimple size considered under study was observed by Ezhilmaran et al [8].

## 8. Conclusion:

The conclusions which can be drawn from the review of the literature survey stated above are as follows,

a. Aspect ratio is an important surface texture parameter to improve the tribological performance of piston ring and cylinder liner pair.

b. Larger dimple depth may be proving harmful under starved lubrication condition.

c. Dimple density should be selected in a proper manner for getting higher performance.

d. Under various operating conditions the dimple depth should be optimized to get good results.

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