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Research Article

Tribological analysis of textured ring-cylinder liner pair under varying operating conditions

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ABSTRACT

Friction reduction at the ring-liner interface significantly enhances internal combustion engine performance. This study investigates the frictional behavior of laser-textured piston ring-liner pairs under varying operating conditions using a friction testing machine. Parameters such as dimple shape (circular, elliptical, rectangular, trapezoidal, non-textured), dimple density (7% to 35%), load (10N to 90N), speed (60 rpm to 1500 rpm), and temperature (30°C to 150°C) were analyzed using a Taguchi L25 array. Results indicate that a circular dimpled ring with 35% density, 90N load, 1500 rpm speed, and 150°C temperature yielded the lowest coefficient of friction, reducing it by 40.81%. Rectangular dimples reduced friction by 60.12% under specific conditions. Elliptical, trapezoidal, and non-textured rings also showed significant friction reduction. Overall, circular dimples at high density, speed, load, and temperature offered the best frictional resistance.

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INTRODUCTION

In an internal combustion engine low thermal and mechanical efficiency are the major concerns along with net energy availability as fuel energy is majorly dissipated in the form of heat as well as friction [1]. Many of the scientists are working on wear and friction analysis of compression piston rings and wall of cylinder liner pair to enhance the performance of the engine [2]. It can be accomplished through proper use of lubricants with additives, surface modification of ring or liner, use of proper coating on it [3]. The engines are working at variable speed, load and temperature conditions throughout all four strokes leads to rapid change in lubricants film thickness [4]. The piston ring experiences a very high normal load during compression and power stroke results into increase in wear and friction [5]. During the initial part of compression as well as combustion stroke ring experiences boundary lubrication, from the mid stoke to top dead center as well as between mid-stroke to bottom dead center at larger load conditions circumstances mixed lubrication is observed [6]. Since from past few years, friction can be reduced by modifying

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the surface with micro textures which plays an important role in friction reduction. These micro textures are generally created intentionally on the surface in the form of cavities or undulations. The lubricant is generally entrapped in these cavities and by providing the hydrodynamic effect it helps in the reduction of the friction. The various studies has been conducted for the evaluation of performance of the textured surfaces but still the behaviour of such surfaces is not very clear [7]. Hence frictional and wear minimization related to dimpled ring and liner needs to be evaluated.

Parul Mishra et al. studied the tribological behaviour of textured piston ring liner system under mixed and boundary regimes and concluded that the average friction coefficient under boundary lubrication was reduced up to 12%. They found that un-textured rings behaves better than the textured ones under hydrodynamic lubrication regime due to extra fluid entrained in dimples. Also concluded that friction reduction of 12% and reduction of wear up to 31% was observed with base oil without additives as the dimples on ring obstructs the appropriate tribochemical film formation from additives in lubricant on the textured surfaces. Hence, additives abolishes the beneficial effect of texturing [7,8]. Yali Zhang et al. studied frictional performance of textured piston rings under different sliding speeds and loads and concluded that rectangular shaped textured rings has shown reduction of average friction coefficient of 36.6% as compared to un-textured rings [9]. V. Ezhilmaran et al. investigated the frictional behaviour of textured ring liner interface and concluded that the optimal value for aspect ratio is 0.2 and for area density is 16% which had given low friction coefficient almost at all loading conditions [10]. Textured ring samples had shown a significant decrease in wear rate of liner at about 72% comparing with non-textured sample. They had also carried out friction trials with micro-channeled piston rings textured from femtosecond and nanosecond laser pulses at 10N to 130 N loads [11]. They observed that coefficient of friction for textured samples was lowered in comparison with non-textured samples [12]. Cong Shen et al. shown that laser pockets led to a reduction of friction up to about 15 % between cylinder liner and piston assembly over a wide range of operating speeds [13]. Atulkumar Patil et al. explored tribological nature of the dimpled ring and cylinder liner pair for a medium passenger vehicle with different dimple shapes like spherical, square by varying loads at 80 N, 150 N and at a constant temperature of 150°C with SAE 20W40 lubricant. They concluded that ring with dimples of spherical shape of 150μm diameter has shown enhanced frictional resistance as compared to ring with dimples of square shape of 150μm size under large loads [14]. Babu et al. explored the effect of protruding texture and reported that texture height of 25μm and area density of 10% has proven better for good wear and friction resistance of positive textured ring-liner interface [15]. Ankit Tyagi et al. used a Taguchi approach for analyzing wear of carbon coating applied on piston ring and concluded that the important factors for wear was sliding speed contributing 59.89%, temperature contributing 28.71% and load contributing 9.18% [16]. Shuwen Wang et al. analyzed the tribological effects of the dimple shape and texture area density on the sliding contacts with dimple shapes like circular, elliptical and grooves of 10% and 20% area density. They concluded that the elliptical dimples found to be suitable for wear reduction, circular dimples found to be suitable for friction reduction and groves proven to be good for friction stabilization [17]. Haytam Kasem et al. studied the frictional responses of the textured stainless steel surfaces with the cast iron counter surface in oil for a sliding contact and concluded that smaller diameter dimples led to a decrease in the coefficient of friction in comparison with larger diameter dimples as well as surface pattern with grids [18]. Amirabbas Akbarzadeh et al. evaluated the running in behaviour and frictional nature of a piston ting with various surface treatments on a specially made engine test rig and found that for a number of steady state and running in experiments combinations of surfaces of piston rings used were coated, textured, coated textured, textured coated and plain out of which the combination of texturing followed by coating had showed enhancement in frictional resistance by 12.5 % and enhancement in break in time up to 50% in comparison with other cases when a single surface modification treatment was used [19]. K. Tripathi et al. investigated the wear and friction nature of grey cast iron textured cylinder liner in lubricated conditions. The friction coefficient of the textured specimen was reduced approximately with 32% in comparison to the specimen with polish. As well as 15% dimple density specimen has shown lowest friction coefficient as compared to all the dimpled specimens working with low as well as high viscosity oils. The oil with high viscosity enhances the frictional resistance and reduces the wear resistance in comparison with the oil with low viscosity [20].

Atulkar et al. compiled the data related to ring liner contact used in an internal combustion engine for studying tribological performances of it in order to save fuel and reduce emissions with the modification of ring surface and studied the combined effect of nano lubricant and partially textured ring [21-26]. They found that with combined effect fuel consumption lowered up to 4.58%, and with only lubricant added with nano particles fuel consumption reduced up to 3.23% [27]. Xiang Rao et al. studied the interactions of various types of surface textures and its effect on friction of ring and liner used in diesel engine at hot conditions. They concluded that proper use of surface textures like 3 mm wide grooves on liner proven to be effective as compared to non-textured surface in order to enhance the performance of engine [28]. R. N. Bathe et al. reviewed the application of texturing with the help of laser to be used for ring and liner contact situations along with its future prospects in vehicle frictional applications in order to get rid of the problems of fuel consumption, emissions and friction [29]. Chenwei Miao et al. investigated the running in nature of textured liner-ring pair with grooves on liner and dimples on ring at

300 N load and speeds of 50 rpm to 100 rpm. They found that dimples on rings acts as mobile oil storage while grooves on liner acts as stationary oil storage which helps in reducing the friction between the pair [30]. Baby et al. (2024) conducted an uncertainty analysis on the friction and wear-rate behavior of cylinder liner-piston ring tribo pairs under boundary lubrication conditions. By considering both measurement and experimental uncertainties, they provided a systematic approach to evaluate tribological performance in engines operating under low lubrication conditions. Their findings underscore the importance of accounting for uncertainties in assessing wear rates and friction, which can lead to more reliable predictions of engine component longevity and performance [31,32]. Wang et al. [33] explored the tribological properties of surface-modified piston rings under extreme conditions. They examined different surface treatments to identify enhancements in friction reduction and wear resistance. Their study demonstrated that specific surface modifications significantly improve performance under high load and extreme environmental conditions. This work is crucial for applications where piston rings are subjected to heavy-duty cycles, as it highlights the potential of surface engineering in enhancing durability and minimizing frictional losses. In another study, Cesur et al. [34] investigated the tribological characteristics of ring-cylinder couplings coated with various materials. By applying different coatings to the piston ring and cylinder liner surfaces, they optimized frictional performance and wear resistance. Their research employed an optimization approach to identify the most effective coating materials, revealing that certain coatings can significantly reduce wear, thereby extending the functional life of the components. This study adds to the body of knowledge by providing a comparative analysis of materials that can mitigate wear and enhance tribological performance in internal combustion engines. Qiu et al. [35] studied the influence of ring materials on the thermodynamic performance of self-lubricating spherical plain bearings. They highlighted how material selection impacts heat generation and distribution, affecting overall tribological performance. Although the focus was on spherical plain bearings, their insights into material thermodynamics and self-lubrication mechanisms are relevant to the development of piston ring-cylinder liner systems where temperature management is critical to maintaining low friction and wear.

With an emphasis on oil feeding conditions, Liu et al. [36] examined the lubricating properties of oil-control rings in connection to cylinder liners. Their results show that friction levels are directly impacted by the oil supply, which also has a significant impact on the lubrication process. According to the study, better oil distribution across the liner-piston interface can lower wear rates and friction, increasing engine efficiency. In high-performance engines, where ideal lubrication is crucial for lowering frictional losses and averting premature wear, our study emphasizes the necessity of accurate oil control systems. Yadvendrakumar Mishra et al. proposed some optimization methods which are beneficial for achieving the responses. They also found that Nd: YAG laser is possibly used to drill geometrically accurate holes in fibre materials [37]. Rita Ferreira et al. [38] used a homemade tribometer to test utilized dimples with varying texture diameters and densities. They had tested the friction coefficient for all the samples under consideration and evaluated the best for wear resistance. The best tribological results were obtained for the texture with a density area of 15% and an aspect ratio of 0.25. Jang S. has found that majority of wear damage and friction loss occur at the top dead center location due to the thin-film thickness caused by slow-down and reversal contact velocities as well as high applied load, hydrodynamic lubrication film formation and pressure between the piston ring and cylinder liner are thoroughly examined. Consideration is given to the cylinder liner's surface roughness from the honing process, which is comparable in size to the thickness of the lubricant coating at the TDC point. They had compared the cylinder surfaces of the honed roughness with those of patterned designs in terms of frictional power loss and minimal film thickness [39-41].

From the above stated comprehensive literature review it has been found that the frictional analysis of laser fabricated textured ring and liner pair operating at varying engine operating conditions like load, speed and temperature along with the varying surface modification parameters like texture shape and texture density was rarely observed. It has also been found that many of the researchers have worked on the textured liners but very rare work has been found on textured ring interacting with liners. Also the various dimple shapes along with varying engine parameters were rarely experimented by the earlier researchers and the said acquaintance has been considered during this research work. Therefore tribological trials of textured ring and liner interface were conducted on reciprocating friction testing machine. The purpose of the study is to study the frictional behaviour of dimpled ring-liner interface at different engine operating conditions in order to find the best possible combination at which the frictional performance will be enhances.

MATERIALS AND METHODS

Specimen Preparation

The Electro Discharge Machining (EDM) process was used to cut the specimens in the form of segments from the commercially available cylinder liner and piston ring pieces used in the gasoline/diesel engines of medium duty passenger vehicles. The Electro Discharge Machining equipment is used for the preparation of specimens is shown in Figure 1. The CAD drawing was used in order to cut both the specimens in an accurate manner as per requirement of the friction testing machine (linear reciprocating parameter).

Figure 1. Electric discharge machining equipment.

The piston ring and cylinder liner is made up of high carbon steel and cast iron respectively. During experimentation piston ring segments of dimensions 5.75mm curved length, 1.5mm thickness and 2.5mm width while cylinder liner of dimensions 25mm curved length, axis length of 35mm were used. The details of profile dimensions and images of cylinder liner and piston ring pair are shown in Figure 1, Figure 2a and 2b.

The chemical composition of various constituents of piston ring as well as cylinder liner material is as shown in Table 1.

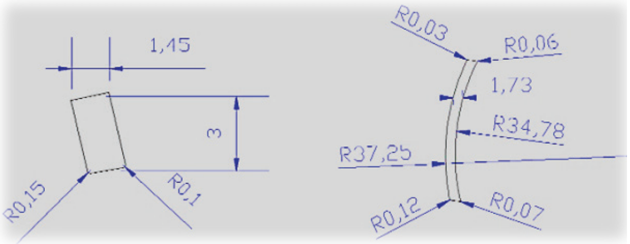


Figure 2a. Profile of piston ring and profile of cylinder liner (dimensions).

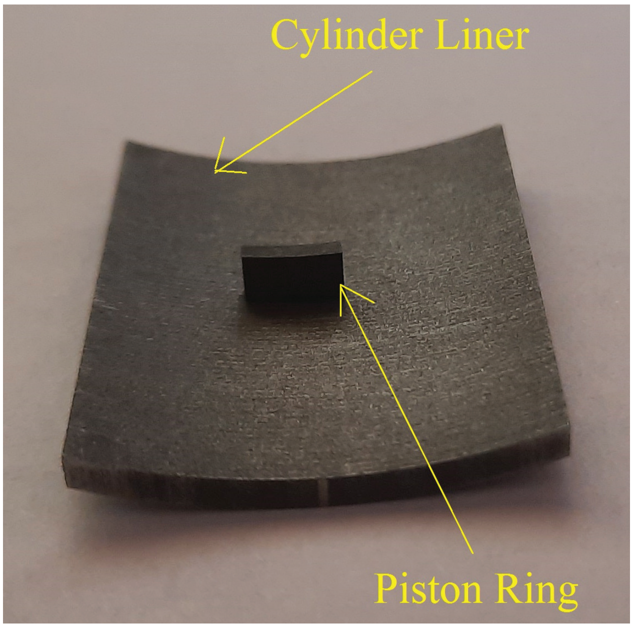


Figure 2b. Piston ring- cylinder liner contact pair.

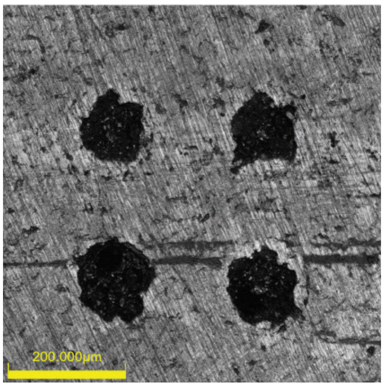
Laser Surface Texturing and Characterization of Textures

The outer surface of piston ring was textured with a nanosecond pulsed commercial laser from Marco Laser Machine, Germany having 20W power, 1064nm wavelength, 20Hz to 200 KHz frequency, maximum laser speed of 15000 mm/s, pulse duration of 26ns to 250 ns. The confocal microscope of Olympus OLS-5000 model was used to characterize the laser texturing details of the ring specimen along with the liner. The details of laser textured piston ring geometric parameters like dimple densities, dimple shape, dimple dimensions etc. are as shown in figure. The various dimple shapes of circular, rectangular, elliptical and trapezoidal were used along with 7%, 14%, 21%, 28% and 35% dimple densities respectively.

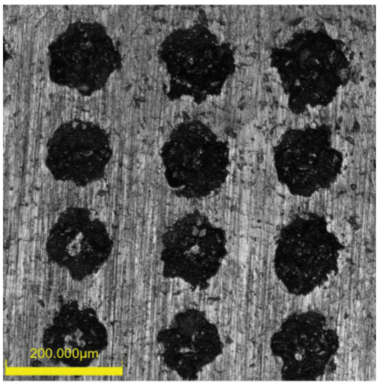
Figure 3 shows the confocal microscope images of some of the textured rings with different dimple shapes along with ring without texture and liner used for the experimentation.

Table 1. Chemical composition of ring and liner

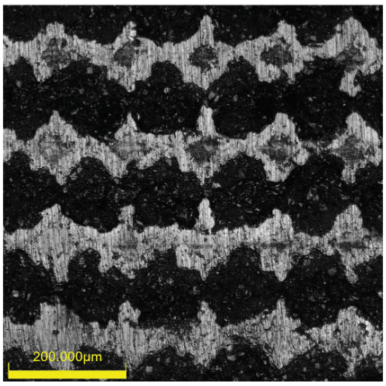
Specimen	Constituents in %					
	C	Mn	Si	P	S	Fe
Piston Ring	3.6	0.80	2.80	0.085	0.043	92.672
Cylinder Liner	2.85	0.58	3.09	0.18	0.072	93.228



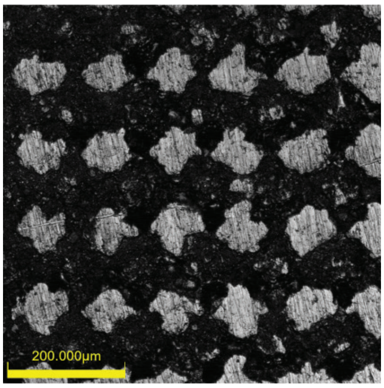
Cir. 7%



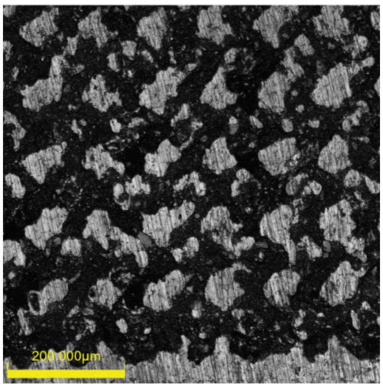
Cir. 14%



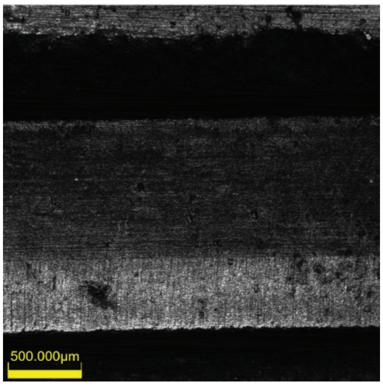
Cir. 21%



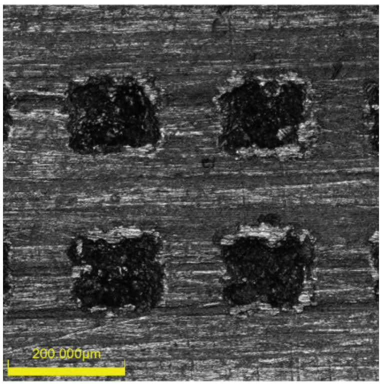
Cir. 28%



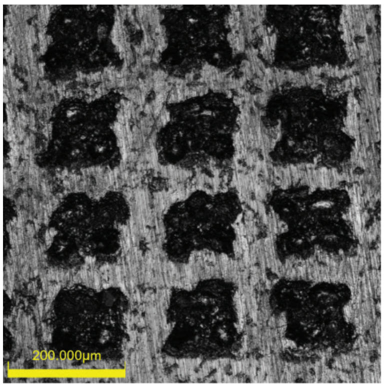
Cir.35%



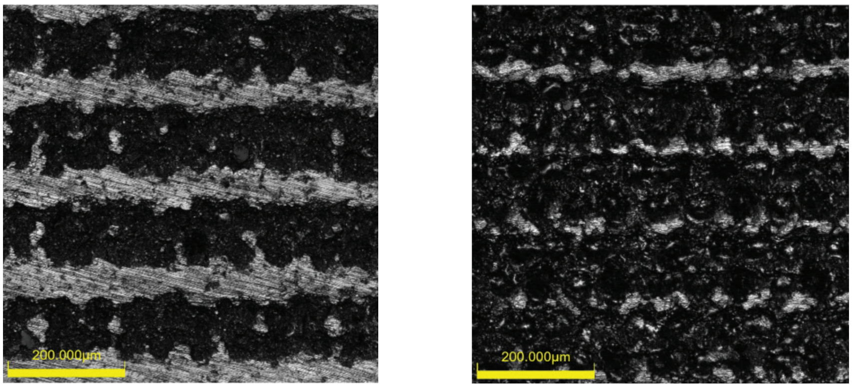
Non Textured Ring



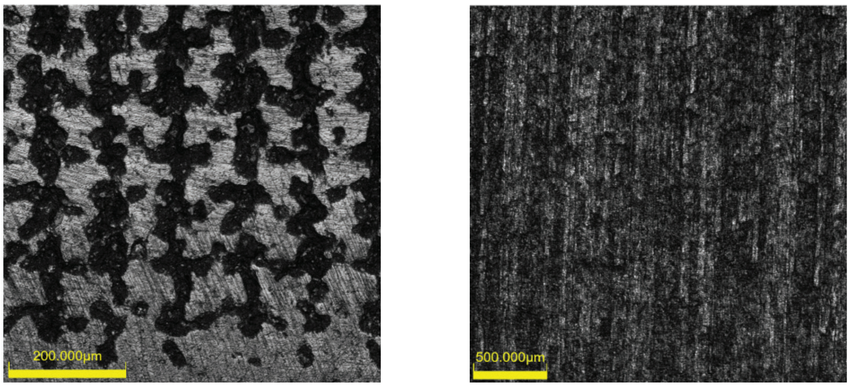
Rect. 7%



Rect. 14%



Rect. 21% Rect. 28%



Rect. 35% Liner before test

Figure 3. Confocal images of laser textured rings and liner.

Experimental Setup

A reciprocating friction testing machine (from Ducom Instruments, Bangalore) which mimics the reciprocating motion of a ring and liner interface, was utilized to analyze the frictional nature of piston rings textured with the help of laser process interacting with liner. The segmented specimens of textured piston ring and regular cylinder liner were fitted in an upper ring and lower liner holders respectively for the testing purpose. During the experimentation textured ring was loaded by the use of a holder exclusively customized for the ring specimens through a circuit operated by air. Normal and lateral force sensors having a very good precision were used to measure the normal and friction forces. The Win-Ducom software was used to collect the test data through a data acquisition system connected to a computer. Figure 4 shows a schematic diagram of an experimental set up with specimen of liner and ring along with the holders.

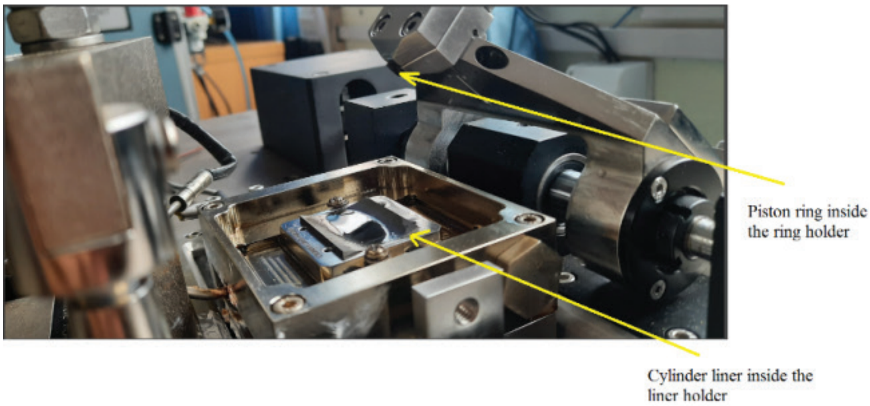


Figure 4. Experimental set up showing ring and liner samples in a linear reciprocating tribometer.

The tribological trials were conducted for 40 minutes of duration by varying various tribological parameters like dimple shape on the textured ring, load, speed and temperature. All the tests were conducted twice and the results were analyzed by averaging the values of frictional force and coefficient of friction. All the three modes of lubrication like boundary, mixed and hydrodynamic were observed during motion of ring and liner interface so as to evaluate frictional behaviour of liner and textured ring at all the modes of lubrication. The tribological test conditions were varied like dimple shape from non-textured, circular, rectangular, elliptical, trapezoidal, dimple density from 7% to 35%, load from 10N to 90N, speed from 60rpm to 1500rpm, temperature from 30°C to 150 °C, oil of SAE5W30, stroke length from 5mm to 25mm, frequency of 5Hz to 25Hz. All the tests were conducted for 40 minutes of duration. ASTM G181-11 standard was used for frictional study of ring and liner interface to conduct the trails. Initially both the test specimens were neatly cleaned with acetone after which dried with the help of air before conducting the trails. The

Table 2. Details of levels and associated control factors

Control Factor	Unit	Level				
		1	**2**	**3**	**4**	**5**
A- Dimple Shape	Type	Circular	Rectangular	Elliptical	Trapezoidal	Non Textured
B-Density	[%]	7	14	21	28	35
C-Load	[N]	10	30	50	70	90
D-Speed	[rpm]	60	480	720	1020	1500
E-Temperature	[°C]	30	60	90	120	150

Table 3. L_{25} orthogonal array of experimental work (5 factors 5 levels)

Trial no.	Dimple shape	Dimple density [%]	Load [N]	Speed [rpm]	Temperature [°C]
1	Circular	7	10	60	30
2	Circular	14	30	480	60
3	Circular	21	50	720	90
4	Circular	28	70	1020	120
5	Circular	35	90	1500	150
6	Rectangular	7	30	720	120
7	Rectangular	14	50	1020	150
8	Rectangular	21	70	1500	30
9	Rectangular	28	90	60	60
10	Rectangular	35	10	480	90
11	Elliptical	7	50	1500	60
12	Elliptical	14	70	60	90
13	Elliptical	21	90	480	120
14	Elliptical	28	10	720	150
15	Elliptical	35	30	1020	30
16	Trapezoidal	7	70	480	150
17	Trapezoidal	14	90	720	30
18	Trapezoidal	21	10	1020	60
19	Trapezoidal	28	30	1500	90
20	Trapezoidal	35	50	60	120
21	Non-textured	N-T	90	1020	90
22	Non-textured	N-T	10	1500	120
23	Non-textured	N-T	30	60	150
24	Non-textured	N-T	50	480	30
25	Non-textured	N-T	70	720	60

proper fixation of both the specimens was done inside the specially made specimen holders of linear reciprocating friction testing machine. The output parameters like frictional force and frictional coefficient of the liner ring interface were noted through a software by Win-Ducom. The characterization of the frictional nature of liner and textured ring interacting surfaces was done with the help of averaging the output parameters of the trails.

Design of Experiments

Taguchi design approach is used for planning the experiments during the study so as to assess the frictional nature of the liner and ring pair [21]. The 5 factors under consideration for the experimental design are dimple shape, dimple density, load, speed and temperature at 5 levels of each [22]. Factors and their respective levels are summarized in Table 2.

The selection of various parameters of dimple shape, dimple density, load, speed and temperature were done by considering the operation of a medium duty passenger car engine as explained in earlier section [23]. As the 5 control factors and 5 levels of each are considered then according to Taguchi's orthogonal array design L_{25} [24-25] orthogonal array was used for the experimentation purpose and the general details of it along with the actual values are as per Table 3. As all of the above experimental trails were carried out at different load, sliding speed and temperature conditions by varying dimple shape and its density to analyze the frictional nature of interface.

RESULTS AND DISCUSSION

All the tribological tests were conducted at various operating conditions like varying dimple shapes, dimple densities, loads, speeds and temperatures therefore the frictional behaviour was analyzed dimple shape wise for all types of dimples with varying operating conditions as specified earlier. The variation of coefficient of friction was plotted against the test duration in seconds for each type of dimple shape with the varying operating conditions. The data of coefficient of friction obtained from the data acquisition system varying as per the time of test was noted for a specific interval of time and used for plotting the graphs as shown in following figures. Following section give the details of variation of frictional coefficient verses time for all types of dimpled ring along with the non-textured one.

Variation of Coefficient of Friction with Circular Dimple Ring

Figure 5 shows the variation of coefficient of friction (COF) of circular dimple ring and liner pair. It can be seen that circular dimple ring with 35% dimple density, at 90N load, 1500 rpm and at 150ºC has shown good frictional resistance as compared to all other rings while sliding against the cylinder liner. Ezhilmaran et al. [10] proved that irrespective of varying texture parameters at dead centers boundary lubrication was observed. As ring moves from dead centers to mid stroke positions it travels with slightly increase in velocity which shifts the lubrication regime from boundary to mixed one. Furthermore when ring attains maximum velocity the lubrication regime shifts to hydrodynamic where a thin film of lubricant exists to lubricate the interacting surfaces [11]. It can be observed that the circular dimple ring-liner interface is operating at 1500rpm which is at a higher speed than the other rings resulted in a hydrodynamic lubrication regime led to minimization of the coefficient of friction due to availability of a reasonable amount of fluid film thickness between the interacting surfaces [10]. Figure 5 also shows that circular dimple ring with 14% dimple density at 30N load, running at 480rpm and 60ºC shows higher coefficient of friction as compared to other rings due to low velocity of sliding resulted into

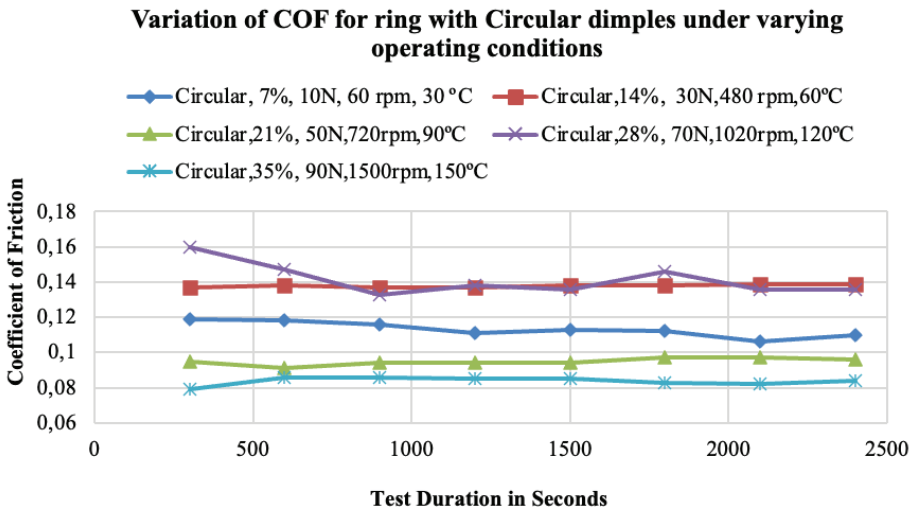


Figure 5. Coefficient of friction versus time for circular shape dimple ring.

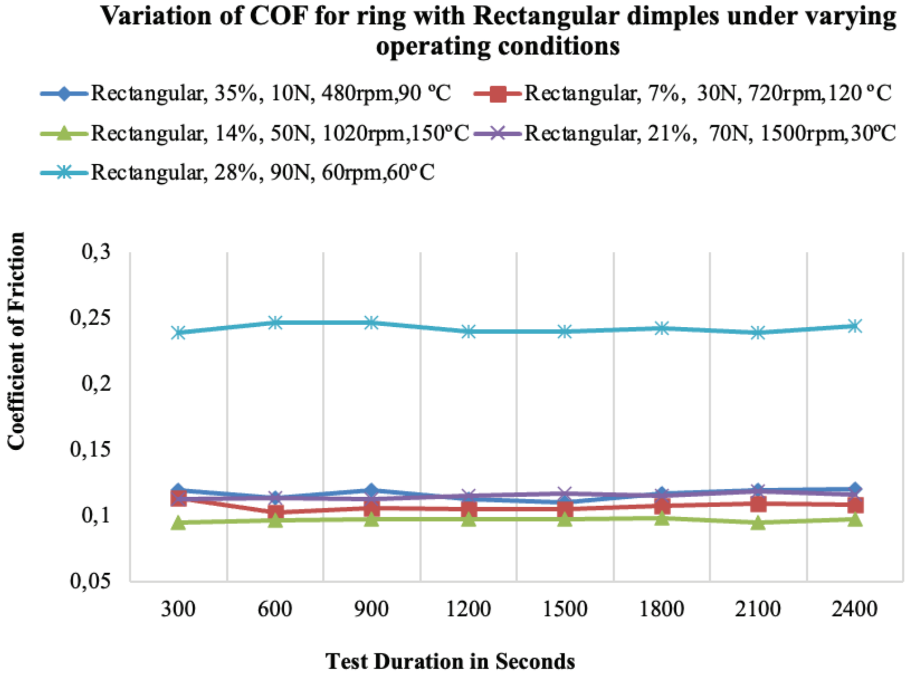


Figure 6. Coefficient of friction versus time for rectangular shape dimple ring.

boundary lubrication regime responsible for raising the coefficient friction [11]. It has been found that nearly 40.81% decrease in coefficient of friction was observed with a circular dimple ring with 35% dimple density, at 90N load, 1500 rpm and at 150°C.

Variation of Coefficient of Friction with Rectangular Dimple Ring

Figure 6 depicts the variation of coefficient of friction of rectangular dimple ring liner pair. It can be seen that rectangular dimple ring with 14% dimple density, at 50N load, 1020rpm and at 150°C has shown good frictional resistance as compared to all other rings. Ezhilmaran et al. [10] concluded that boundary lubrication was observed at dead centers irrespective of varying texture parameters. As ring moves from dead centers to mid stroke positions it travels with slightly increase in velocity which shifts the lubrication regime from boundary to mixed one. Furthermore when ring attains maximum velocity the lubrication regime shifts to hydrodynamic where a thin film of lubricant exists to lubricate the interacting surfaces [11]. It can be observed that the rectangular dimple ring-liner interface is also operating at 1020 rpm which is nearly at a higher speed than the other rings resulted in a hydrodynamic lubrication regime led to minimization of the coefficient of friction due to availability of a sufficient amount of fluid film thickness between the interacting surfaces [10]. Figure 6 also shows that ring with dimple density of 28% at a load of 90N running at 60rpm and 60°C shows enhanced coefficient of friction because a pure boundary lubrication regime as it is rotating at a very low speed of 60 rpm which had lowered the lubricant film thickness tends to have increase in coefficient friction [11]. It has been found that nearly 60.12% decrease in coefficient of friction for rectangular dimpled ring with a dimple density of 14%, at a load of 50N, running at a speed of 1020rpm and at 150°C.

Variation of Coefficient of Friction with Elliptical Dimple Ring

Figure 7 shows the variation of coefficient of friction of elliptical dimpled ring-liner pair. The elliptical dimple ring with 21% dimple density, loaded with 90N, running at 480rpm and operating at 120°C has shown good frictional resistance as compared to all other rings sliding against the cylinder liner. Ezhilmaran et al. [10] concluded that boundary lubrication was observed at dead centers irrespective of varying texture parameters. As ring moves from dead centers to mid stroke positions it travels with slightly increase in velocity which shifts the lubrication regime from boundary to mixed one. Furthermore when ring attains maximum velocity the lubrication regime shifts to hydrodynamic where a thin film of lubricant exists to lubricate the interacting surfaces [11]. This case implies that running speed of 480rpm which is very closer to boundary lubrication regime but still shows a good frictional resistance because here the dimple density of used dimple is of 21% which gives sufficient dimpled area to store the lubricant in it which may be available during the sliding of the surfaces by forming a sufficient lubricant film thickness between the interacting pair led to reduction in friction [12]. It can be observed that ring with 14% dimple density at 70N load running at 60rpm and 90°C shows very poor frictional

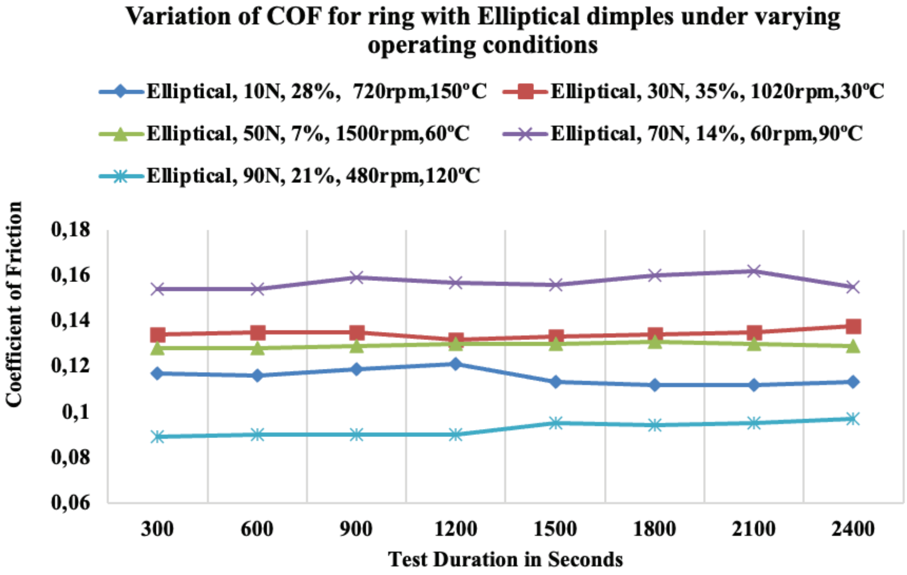


Figure 7. Coefficient of friction versus time for elliptical shape dimple ring.

resistance due to pure boundary lubrication regime which had decreased the lubricant film thickness which had led to enhancement of frictional coefficient [11]. It has been found that nearly 41.12% decrease in coefficient of friction for elliptical dimple ring with 21% dimple density, loaded with 90N, running at 480rpm and operating at 120°C.

Variation of Coefficient of Friction with Trapezoidal Dimple Ring

Figure 8 shows the variation of coefficient of friction of trapezoidal dimple ring-liner. The trapezoidal dimple ring with 28% dimple density loaded at 30N, running at 1500rpm and operating at 90°C has shown good frictional resistance as compared to all other rings sliding against the cylinder liner. Ezhilmaran et al. [10] concluded that boundary lubrication was observed at dead centers irrespective of varying texture parameters. As ring moves from dead centers to mid stroke positions it travels with slightly increase in velocity which shifts the lubrication regime from boundary to mixed one. Furthermore when ring attains maximum velocity the lubrication regime shifts to hydrodynamic where a thin film of lubricant exists to

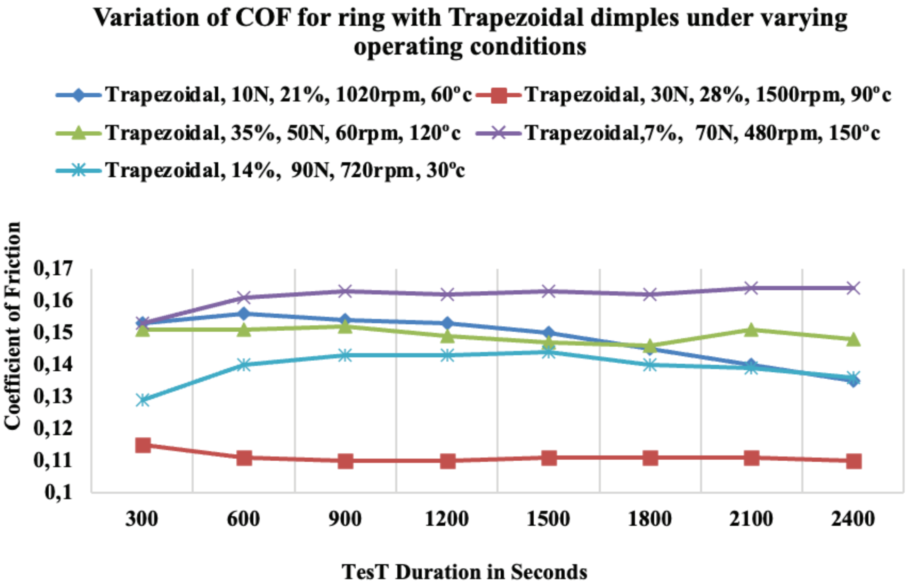


Figure 8. Coefficient of friction versus time for trapezoidal shape dimple ring.

lubricate the interacting surfaces [11]. In this case also it may be observed that the trapezoidal dimple ring-liner interface which is operating at 1500 rpm resembling the hydrodynamic lubrication regime led to minimization of the coefficient of friction of the pair due to availability of sufficient amount of lubricant at the interface [12]. It can be observed from the trapezoidal ring with 7% dimple density at 70N load, running at 480rpm and 150°C shows poor frictional resistance as the pair observed boundary lubrication regime due to low speed of rotation which had reduced the film thickness of lubricant and in turn responsible for the enhancement of the frictional coefficient [11]. It has been found that nearly 31.19% decrease in coefficient of friction for trapezoidal dimple ring with 28% dimple density loaded at 30N, running at 1500rpm and operating at 90°C.

Variation of Coefficient of Friction with Non-Textured Ring

Figure 9 shows the variation of coefficient of friction for non-textured ring-liner pair. The non-textured ring loaded with 90N, running at 1020rpm and at 90°C has shown good frictional performance as compared to all other non-textured rings while sliding against the cylinder liner. Ezhilmaran et al. [10] concluded that boundary lubrication was observed at dead centers irrespective of varying texture parameters. As ring moves from dead centers to mid stroke positions it travels with slightly increase in velocity which shifts the lubrication regime from boundary to mixed one. Furthermore when ring attains maximum velocity the lubrication regime shifts to hydrodynamic where a thin film of lubricant exists to lubricate the interacting surfaces [11]. It can be observed that the ring liner interface is operating in a hydrodynamic lubrication regime as it is operating at 1020rpm at higher loading conditions which had led to minimization of the coefficient of friction [10]. Also the non-textured ring with loaded by 30N, running at 60rpm and 150°C shows higher coefficient of friction because as the interacting pair slides in a pure boundary lubrication mode due to very low running speed of 60 rpm which had lowered the lubricant film thickness and enhanced the frictional coefficient [11]. It has been found that nearly 82.21%decresae in coefficient of friction for non-textured ring loaded with 90N, running at 1020rpm and at 90°C.

Figure 10 shows theComparative analysis of different dimple shapes (circular, rectangular, and elliptical) with varying dimple densities. The optimal configurations, as indicated, include Circular Dimples with 35% dimple density, Rectangular Dimples with 14% dimple density, and Elliptical Dimples with 21% dimple density, demonstrating improved surface characteristics. The study reveals that dimple shape and density play a crucial role in determining the surface characteristics and tribological performance of the material. Among circular dimples, a higher density of 35% exhibits superior performance compared to 14%, indicating enhanced lubricant retention and reduced friction. For rectangular dimples, the 14% dimple density performs better than the 28% density, suggesting that an optimal balance between surface contact and lubricant trapping is essential. In the case of elliptical dimples, a moderate increase in density to 21% results in improved performance compared to 14%, demonstrating that a well-calibrated density enhances lubrication efficiency without excessive surface modification. Overall, the optimal dimple configurations identified for enhanced tribological behavior are 35% density for circular dimples, 14% for rectangular dimples, and 21% for elliptical dimples. These findings highlight the importance of selecting appropriate dimple shapes and densities to optimize wear resistance and lubrication efficiency.

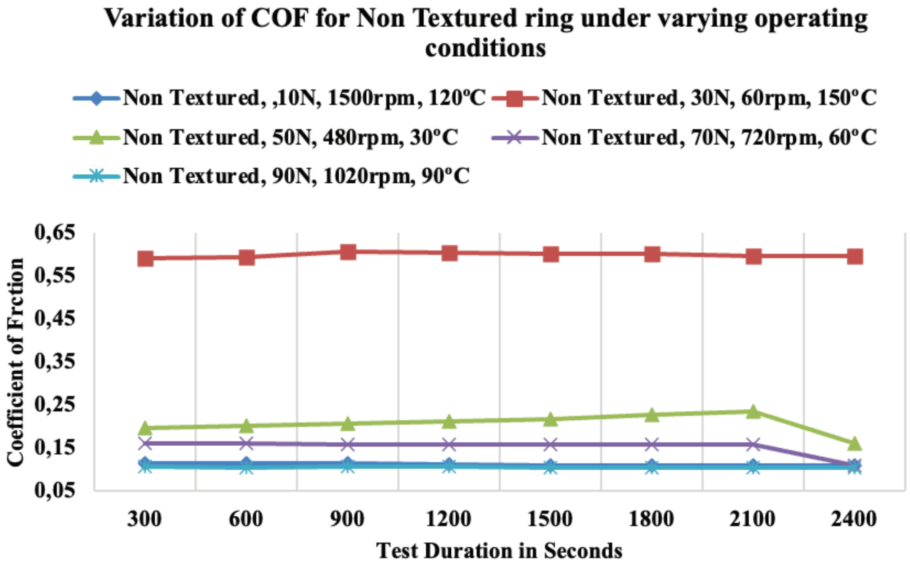
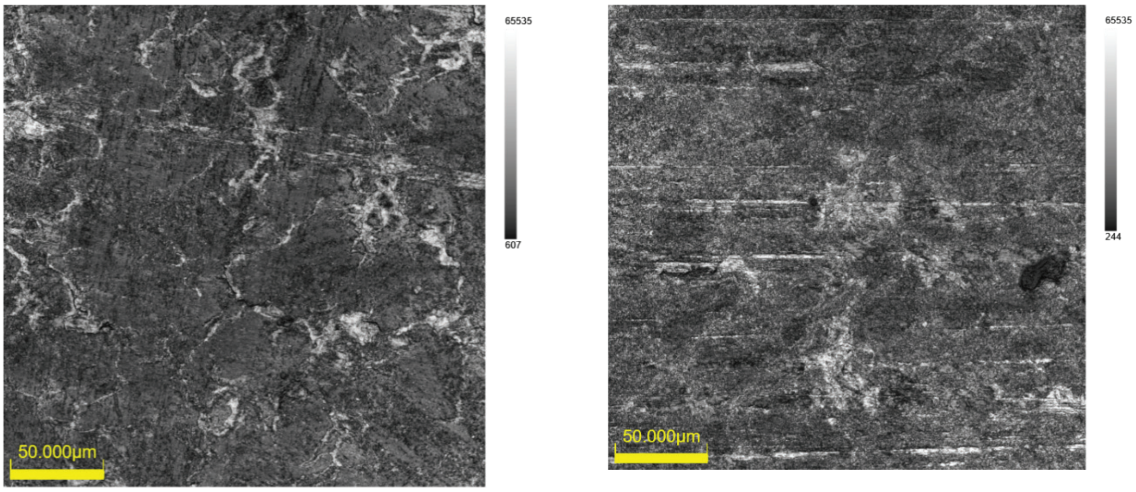
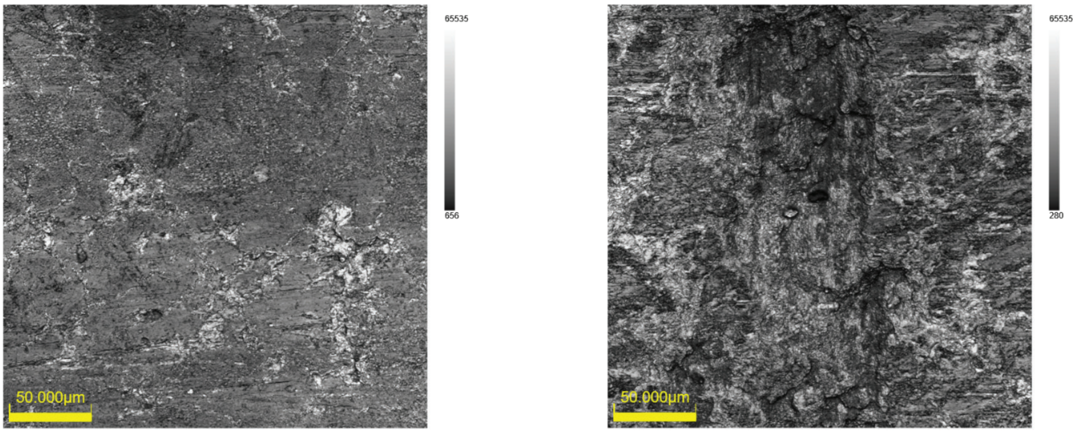


Figure 9. Coefficient of friction versus time for non-textured ring.



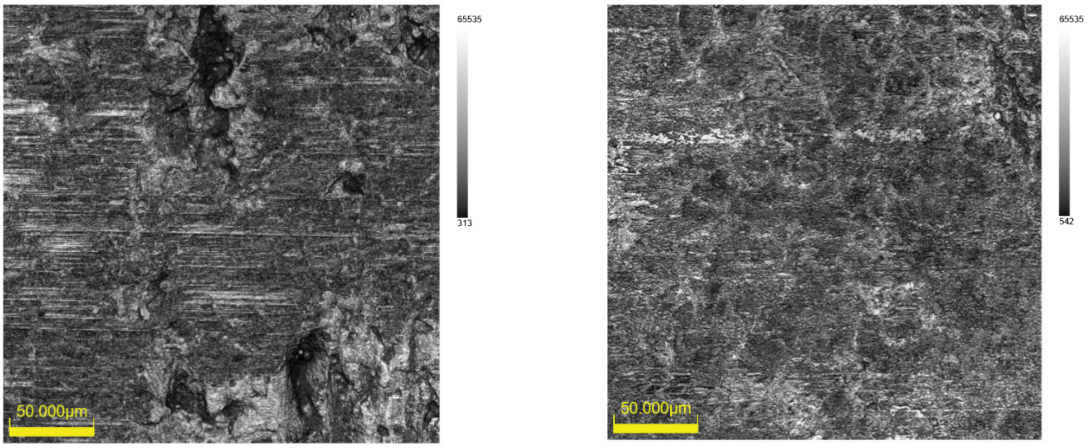
a)Circular dimple with 14% dimple density

b) Circular dimple with 35% dimple density (good)



c) Rectangular dimple with 14% dimple density (good)

d) Rectangular dimple with 28% dimple density



e) Elliptical dimple with 14% dimple density

f) Elliptical dimple with 21% dimple density (good)

Figure 10. Optical microscopy images of elliptical dimple with different dimple density.

CONCLUSION

The frictional analysis of laser surface textured ring-liner pair was carried out at varied operating conditions of dimple shape, dimple density, load, speed and temperature by considering the reference of medium duty passenger car engine. The following concluding remarks can be summarized for the work under consideration.

- Dimple shape and dimple density are playing a vital role in analyzing the frictional performance of textured ring and liner pair and which must be selected properly as per the application of engine.
- The circular dimple shape and the dimple densities of 28% and 35% are proving better for reducing the friction coefficient of the textured ring and liner interface.
- The sliding velocity/speed of rotation of the interacting pair and applied load on the ring are also very significant factors while analyzing the performance of the pair.
- It can be observed that except trapezoidal ring-liner pair all other pairs have given a good frictional resistance nearly at higher loading conditions like 50N and 90N.
- It can also be observed that except elliptical ring-liner pair all other pairs have given a good frictional resistance nearly at higher operating speeds like 1020rpm, 1500 rpm etc. which corresponds to hydrodynamic lubrication mode.
- It can be observed that dimple density for a textured ring-liner pair with 21% and 35% found better performer for circular and elliptical dimple ring respectively while textured ring-liner pair with 14% and 28% found better performer for rectangular and trapezoidal dimple ring respectively.
- It has been found that nearly 40.81% decrease in coefficient of friction was observed with a circular dimple ring with 35% dimple density, at 90N load, 1500 rpm and at 150°C.
- It has been found that nearly 60.12% decrease in coefficient of friction for rectangular dimpled ring with a dimple density of 14%, at a load of 50N, running at a speed of 1020rpm and at 150°C.
- It has been found that nearly 41.12% decrease in coefficient of friction for elliptical dimple ring with 21% dimple density, loaded with 90N, running at 480rpm and operating at 120°C.
- It has been found that nearly 31.19% decrease in coefficient of friction for trapezoidal dimple ring with 28% dimple density loaded at 30N, running at 1500rpm and operating at 90°C.
- It may be concluded in general that considering the individual effect of various dimples fabricated on the ring outer surface, the frictional nature of the liner and textured ring pair has improved at nearly medium to higher dimple density, higher speed of rotation, higher loading conditions and at higher operating temperatures.

Limitations and Future Scope

This study has been carried out at simulated operating conditions therefore it is having some limitations like the availability of combustion and allied factors but the load applied at the back of the ring, speed of rotation and the temperature has been simulated as per the engine under consideration. Also due to experimental set up limitation the speed has been considered up to 1500 rpm which is somewhat smaller than the real engine conditions but still it is sufficient one for analyzing the performance of the pair. Though there are certain limitations for the study under consideration still the results will be surely helpful to the engine component designers, researchers in the concern domain. The future work like the testing of laser textured ring in an actual engine and evaluating its tribological performance will be of great help but which may require more amount of funding. Also the future work like tribological evaluation of texture ring and liner pair with combination of circular, elliptical, rectangular and trapezoidal textures on a single ring and liner as its counterpart may be the another area to be considered.

ABBREVIATIONS

EDM	Electric Discharge Machining
ASTM	American Society for Testing of Materials
SAE	Society of Automotive Engineers
COF	Coefficient of Friction

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

STATEMENT ON THE USE OF ARTIFICIAL INTELLIGENCE

Artificial intelligence was not used in the preparation of the article.

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