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FRICTIONAL POWER MINIMIZATION IN PARTIALLY TEXTURED PISTON RING ASSEMBLY

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Abstract - A significant share i.e. 60% of the total power loss in a modern automotive engine in form of heat, either from the engine surface or the exhaust pipe, of which the friction losses may vary from 18% to 20% and frictional losses are also responsible for about 25% of the fuel consumption. It is noted that almost 80% of the frictional losses are due to the frictional losses in the piston ring assembly (PRA). That leaves less than one quarter of the indicated power in terms of brake power. This paper analyses different methods developed by the automobile industries in order to reduce the friction power losses it may be in form of the development of better lubricants, design and partial laser surface texturing (LST) of the piston rings.

Keywords - *Piston ring assembly (PRA), Frictional power, Lubricants, Partial laser surface texturing.*

I. INTRODUCTION

Many research works deal with the problem of engine friction force in general and piston rings friction in particular. This is because most of the total engine friction, about (50- 60%), comes from the piston-cylinder group. Friction, and friction in general, can roughly be compartmentalized into two groups: coulomb friction (dry friction) which occurs when asperities come into contact between two surfaces moving relative to each other and fluid friction which develops between adjacent layers of fluid moving at different velocities. The actual degree of friction in engine components can seldom be put into either of these categories, and instead lies somewhere between these two extremes. That is to say, there is a continuum between dry friction and fluid friction and the placement on this continuum is dependent on such factors as: component geometry, surface roughness, relative velocities of the moving surfaces, normal loads, and various rheological properties of the lubricant.

It is known that the tribological behavior of the piston ring has a major role in influencing the performance of the internal combustion engine in terms of frictional power losses, fuel consumption and exhaust emissions .A significant share of the total power loss (Figure 1) in a modern automotive engine is due to the upper compression ring/cylinder wall friction. On this basis, the lubrication of the piston ring has been an important research matter for many years because it is extensively accepted that the interaction at the ring-cylinder wall interface provides substantial effects on friction, wear, oil consumption and power loss in ICEs. The most common arrangement is a set of three rings (Figure 2), the upper compression ring, the lower compression ring and the oil control ring.

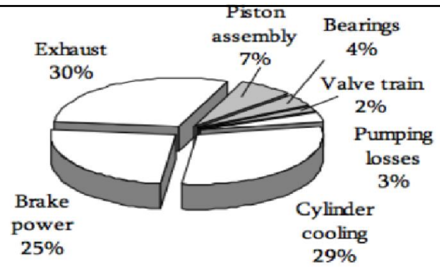

Figure 1: fuel energy in an internal combustion engine (friction losses in grey, 4 krpm, full load)

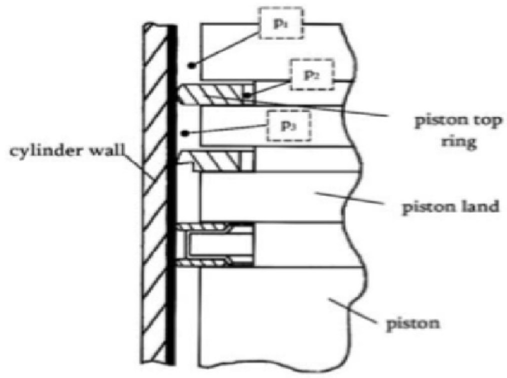

Figure 2: geometry of the lubricated pair piston rings-cylinder wall

Proper lubrication and surface texture are key issues in reducing friction in a piston/cylinder system and, hence, have received a great deal of attention in the relevant literature. Surface texturing as a means for enhancing tribological properties of mechanical components has been well known for many years. Surface texturing in general and laser surface texturing (LST) in particular has emerged in recent years as a potential new technology to reduce friction in mechanical components.

II. PARTIAL LASER SURFACE TEXTURING OF PISTON RINGS

It is well known that friction forces present an essential factor in fuel consumption and performance of the engine. It was established that about 40 percent of the friction losses of the engine are due to the contact of the piston ring and liner, so a reduction of this force is crucial.

The texturing of the rings has two positive effects

- The reduction of friction between the piston and the rings.
- The good functioning in conditions of “starvation”, because of the properties of oil retention of the dimples.

By surface texturing, the friction coefficient decreases by 20 to 30 percent [5,6,11]. In the fig.3 a textured piston ring is presented. Studies have also shown that friction can be reduced when surface dimples are added even when no contact occurs. Etsion. have completed several analytical and experimental studies considering the effects of round dimples on sliding friction and load support. Early studies, based on a CFD model in which contact was not considered, predicted increased load support in face seals with the addition of dimples, where the ratio of depth: diameter was the main factor in optimizing the texturing.

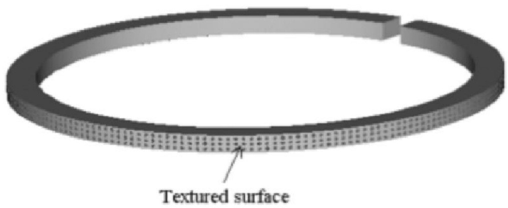

Fig. 3 : Laser Textured Piston Rings

Surface texturing as a means for enhancing tribological properties of mechanical components has been well known for many years. Perhaps the most familiar and earliest commercial application of surface texturing in engines is that of cylinder liner honing (Jeng (1); Willis (2)).

Laser surface texturing (LST) has emerged in recent years as a potential new technology to reduce friction in mechanical components (Ryk. (3); Etsion. (4); Kligerman and Etsion (5); Ronen. (6)). Ronen. (6) developed a theoretical model for a piston/cylinder system with LST piston rings. The authors studied the potential use of piston-ring micro-surface structure in the form of spherical micro-dimples to reduce the friction between rings and cylinder liner where the entire ring face in con- tact with the cylinder liner was textured. It was demonstrated that this surface texturing even with nominally parallel mating surfaces could generate a significant hydrodynamic effect. The time variation of the clearance between the piston ring and cylinder liner and the friction force for any given operating conditions were obtained by simultaneously solving the Reynolds equation and a dynamic equation of the ring radial motion. The main parameters of the problem were identified as the area density of the dimples, dimple diameter, and dimple depth. An optimum value of the micro-dimple depth over diameter ratio was found, which yields a minimum friction force. It was found that a friction reduction of 30% and even more is feasible with a textured ring surface. The model prediction was experimentally verified by Ryk. (3).

Laser texturing has enormous potential for increasing efficiency and durability of these engines. Specific components that can benefit from laser texturing are piston rings and liners, tappets, cam and follower interface, gear systems, water pump seals, and other bearing systems. Many of these components operate under different lubrication regimes during actual engine uses; hence, combining laser texturing with advanced coating technologies may have beneficial synergistic effects on friction and wear. Specifically, such coatings on textured surfaces may further reduce friction and wear and prevent scuffing under severe loading conditions, where direct metal-to-metal contact occurs.

The dimples created by pulsating laser beams on a surface are typically 4-10 µm deep and 70 to 100 µm wide. During the dimpling process, material melts and/or evaporates to create the dimples. A portion of the molten material is accumulated around the edges of the dimples and requires post-process removal; otherwise, the dimples can cause severe wear and high frictional losses during sliding contacts.

The micro dimples created by this method can act as miniature hydrodynamic bearings that reduce friction and wear by increasing the load-bearing capacity and, hence, the hydrodynamic efficiency of such sliding surfaces. They can also trap wear debris particles that generate during sliding contacts and hence prevent them from causing third-body wear. Accordingly, the primary objective of this project is to produce and further optimize the size, shape, and density of shallow dimples on sliding and rotating contact surfaces and to explore their effectiveness in reducing friction and wear in critical engine components. Furthermore, synergistic effects of soft and hard coatings on friction and wear of laser-dimpled surfaces are explored.

Two LST modes are available to reduce the friction losses and improve tribological performance of mechanical components. The first one is the full-width LST mode, which is based on an individual dimple effect (local cavitation in each dimple; e.g. Etsion (4)). The second mode is a partial LST, which is based on a so- called collective effect of the dimples that provides an equivalent converging clearance between nominally parallel mating surfaces (similar to the “inlet roughness” concept of Tonder (7)). This collective effect of the partial LST was demonstrated by Etsion and Halperin (8) for high-pressure hydrostatic mechanical seals, and by

Brizmer. (9) for parallel thrust bearings. It was shown theoretically by Brizmer. (9), and verified experimentally by Etsion (10), that partial LST significantly increases the load-carrying capacity compared to full LST.

More recently, Kligerman (11) developed an analytical model of partial LST flat piston rings. They found that the friction for the optimum partial LST piston rings is significantly lower than that for the corresponding optimum full LST rings. The difference varies from about 30% reduction for narrow rings to about 55% reduction in wide rings. The main purpose of the present article is to examine experimentally the finding of Kligerman (12) regarding the potential benefit of using partial instead of full LST for friction reduction in piston rings.

Three series of tests were carried out to study the benefit of partial LST in friction reduction of the textured specimens. The first of them consists of untextured specimens to establish a reference, the second utilized full LST specimens for comparison, and the third was performed with partial LST specimens. The LST parameters were selected based on the optimum results from the models of the full and partial LST of Ronen (6) and Kligerman (11), respectively, and the experience gained in previous tests (Ryk. (3)). These parameters were 78 µm dimple diameter, 9 µm dimple depth, and 10% area density for full LST, and 75 µm dimple diameter, 7 µm dimple depth, and 50% area density for partial LST. It was shown by Kligerman. (11) that in partial LST an optimum textured portion (the ratio Bp/W∗ in Fig. 4) of 0.6 holds for a wide range of LST parameters and operating conditions of the piston-ring/cylinder system simulation. Hence, a textured portion of 0.6 was applied to all the partial LST specimens symmetrically at their ends (see Fig. 4.b).

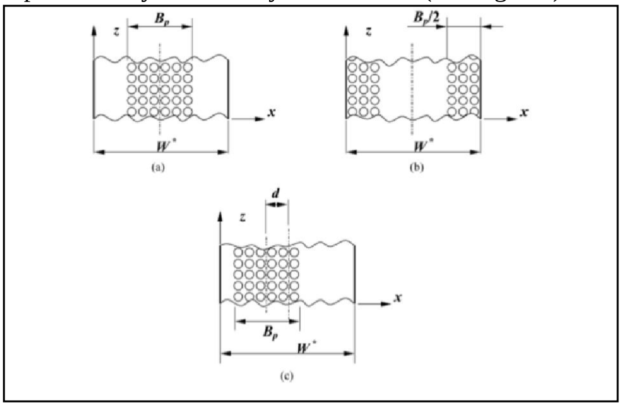

Fig. 4 : Different locations of the textured zone: (a) symmetrically in the center, (b) symmetrically at both ends, and (c) arbitrarily at a distanced from the ring center.

The angular velocities are shown in Fig.5 for the reference untextured case and for the two modes of full and partial LST cases. As can be seen, the average friction increases with speed and load in all three cases as would be expected. Clearly the LST has a substantial effect on friction reduction compared to the untextured reference case. The average friction obtained with the full LST is about 40 to 45% lower than in the reference case at low speeds around 500 rpm, and 23 to 35% lower at higher speeds around 1200 rpm. These percentage differences between the average friction in the untextured and full LST cases are almost independent of the external normal load and slightly decrease with increasing angular velocity.

The results in Fig.4 clearly show the additional reduction in friction that can be obtained with partial LST over that of the full LST case, as was predicted by Kligerman. (12). This additional reduction varies from 12 to 29% depending on the load and speed. In the present test, the maximum benefit of the partial LST was obtained with the combination of lowest speed and highest load. Table 1 summarizes the percentage gain in friction reduction with partial LST compared to full LST at the three load levels and at the extremes of the angular velocity range. As can be seen from Table 1, at the lowest speed of 500 rpm the behavior is very consistent, showing improving partial LST performance with increasing external loading. The behavior is somewhat random at the highest speed of 1200 rpm but still shows at least 12% gain with the partial LST. The different behavior at 1200 rpm could be attributed to the fact that above 900 rpm the vibration level of the test rig starts to increase and above 1200 rpm it reaches a high enough level to prohibit testing in this speed range. Hence, the friction measurements at 1200 rpm can be considered less reliable than at the 500 to 900 rpm range.

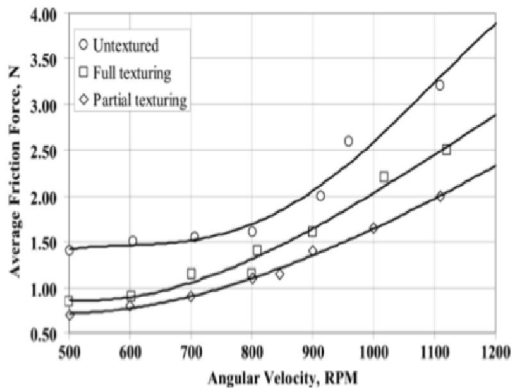

Fig. 5 : Time-averaged friction force vs. crank angular velocity for external normal pressure 0.1 MPa.

TABLE 1—PERCENTAGE GAIN IN FRICTION REDUCTION WITH PARTIAL LST COMPARED TO FULL LST

	0.1 MPa	0.3 MPa	0.5 MPa
500 rpm	12%	23%	29%
1200 rpm	19%	12%	16%

III. LUBRCATION IN LST PISTON RINGS

The piston ring-pack contributes a large portion of the mechanical losses in an internal combustion engine. In this study, the effects of lubricant viscosity are evaluated with the goal of reducing these mechanical losses.

The ring can experience three modes of lubrication - hydrodynamic, mixed, and boundary - illustrated in Figure 6. In pure hydrodynamic lubrication, there is no contact between the ring and liner, and the ring load is entirely support by hydrodynamic pressure in the oil film. In this regime, the ring/liner friction results entirely from shear stress within the oil. In pure boundary lubrication, the entire ring load is support by solid-solid contact between the ring and liner, with no hydrodynamic contribution. In this case, ring/liner friction consists entirely of rubbing friction losses. When the ring load is partially supported by the oil pressure, and partially by asperity contact, mixed lubrication occurs. In this situation, friction losses stem from both oil shear and metal- metal rubbing.

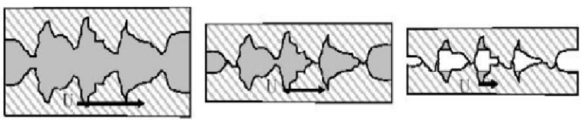

Fig. 6 : Modes of ring lubrication

Oil viscosity affects friction directly in the hydrodynamic regime, where hydrodynamic friction increases with viscosity. It also influences boundary friction indirectly via oil film thickness – higher viscosity causes oil films to be thicker, which reduces asperity contact. At the optimum viscosity (the viscosity at which minimum friction losses are incurred) there is a balance between these hydrodynamic and boundary effects.

As piston speed, ring loading, and other parameters change during the engine cycle, the optimum oil viscosity also changes. If the variation of viscosity could be controlled during the cycle, it could be maintained at an optimum at all times. In this study, several theoretical and realistic cases were studied to quantify the friction benefit that could be obtained if this were possible.

Textured surfaces create a lubrication film, which produces a load carrying capacity when there is no condition for the wedge effect. This phenomenon can have a large variety of industrial applications: it improves the functioning of mechanical seals, it can be used to manufacture partial textured thrust bearings, also it leads to an improvement of fuel consumption in the case of internal combustion engines by texturing the rings or the liner and by texturing the cage of cylindrical roller bearings their durability increases.

Friction and wear testing of laser-textured surfaces was performed in a pin-on-disk machine by the Argonne National Laboratory in 2005.The test generated a series of lubrication maps showing the regions where full hydrodynamic as well as mixed lubrication can be achieved with the laser-textured surfaces. Fig.7 shows that with laser-textured surfaces, the hydrodynamic regime has been greatly expanded to cover almost all of the load and speed ranges evaluated in this study. For un-dimpled surfaces, however, the hydrodynamic regime could only be maintained under light loads and at high speeds. These results can clearly illustrate the beneficial affects of laser texturing on controlling friction even under severe sliding conditions. We believe that shallow dimples created on the sliding surfaces increased the load-bearing capacity of these surfaces by acting as miniature hydrodynamic bearings and thus reduced friction. Microscopic inspection of sliding surfaces after the sliding tests has revealed very little wear (mostly in the form of minor scratches) on these surfaces, while significant wear damage had occurred on the un-dimpled surfaces. We feel that the superior wear performance of dimpled surfaces may have been primarily due to the fact that very few metal-to-metal contacts had occurred on dimpled test pairs. Furthermore, any wear debris that may have been generated during sliding contact was trapped within the dimples, and hence third-body wear did not take place on dimpled surfaces.

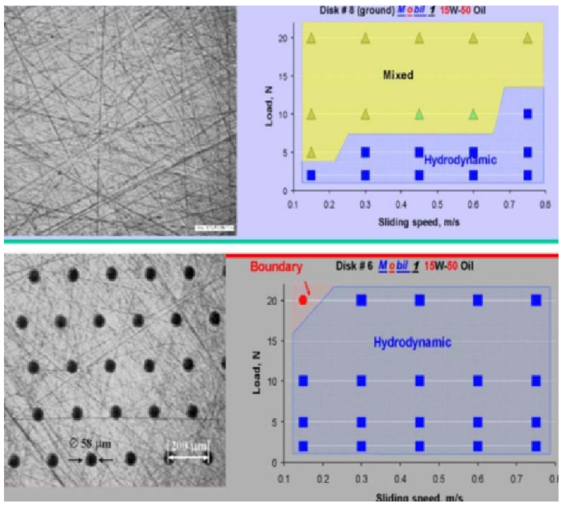

Fig.7 : Comparison of lubrication performance of un-textured (top) and laser-textured (bottom) surfaces.

Like large scale converging surfaces, micro-scale asperities can create an asymmetric oil pressure distribution that results in hydrodynamic lift. In cases of mixed lubrication, this added lift can alter the balance between hydrodynamic and boundary lubrication, reducing the amount of asperity contact that takes place, and thus reducing both friction and wear. Also, even when contact does not occur, an increase in oil film thickness reduces shear within the oil, reducing hydrodynamic friction. Several studies, both analytical and experimental, have considered the effects of surface patterns in hydrodynamically lubricated cases.

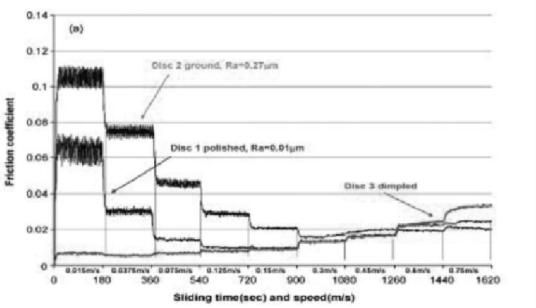

Fig. 8: Adding dimples delayed the onset of asperity contact in this test, from Kovalchenko, et. al. [12]

Because they can assist in creating hydrodynamic pressure in the fluid film, textured surfaces have an effect on the lubrication regime of sliding surfaces. Kovalchenko et.al. looked closely at the lubrication regime effect in a series of experiments using a pin-on-disk test rig with unidirectional sliding, with a textured disk.[12] This study produced Stribeck- like curves for various lubricants and load conditions, and different dimpled area densities (the depth: diameter ratio for the dimples was maintained at an “ideal” value in all cases). In general, dimpling expanded the range of parameters under which hydrodynamic lubrication took place, extending the non-contact regime to low speeds and viscosities. An example of Kovalchenko’s results is shown in Figure 8.

Surface dimples or grooves may act as lubricant reservoirs or as wear particle traps, and possibly in other capacities as well. Study of these phenomena would help answer questions as to what textures are appropriate for the cylinder liner, where they should be placed, etc. For example, it has been suggested that dimples be placed on the liner near TDC to act as lubricant reservoirs for the top ring. Modeling the effectiveness of such dimples would inform the choice of using these or other textures.

IV. CONCLUSION

Partial laser texturing of the piston rings of the internal combustion engine is advantageous in every possible way. Using the LST piston rings has ensured the reduction in frictional power losses by 40-50% in lower RPM and 12-15% at higher rpm when compared to the traditional untextured rings, this will increase the amount of usable power significantly and reduce fuel consumption per brake horsepower to a large extent. And the minimum average friction force for the optimum partially textured piston ring is significantly lower than that for the corresponding optimum fully textured ring. The difference varies from about 30% reduction for narrow rings to about 55% reduction in wide rings.

The effect of surface patterns on friction in the hydrodynamic regime was evaluated. Friction reduction was observed when the surface texturing caused an increase in flow resistance, increasing oil film thickness and thus causing a reduction in both asperity contact and hydrodynamic friction. (In the latter case, the increased film thickness causes a reduction in oil shear rate). A parametric analysis of both grooved and dimpled patterns was performed, with the two purposes of studying the effects of various geometrical parameters on this friction reduction, and evaluating the potential of textured surfaces to reduce ring/liner friction and possibly justify further research in this area.

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