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OPTIMIZING TOP PISTON RING IN IC ENGINES FOR HIGH SEALING PERFORMANCE CONCOMITANT TO IMPORTANTLY REDUCED FRICTION, WEAR, OIL CONSUMPTION AND HARMFUL EMISSIONS

Adina C. CUCU, *
Carol CSATLÓS, **

* Diplomat Eng., Research Scientist, European M.Sc., PhD student, TRANSILVANIA U. of Brasov, Romania, ** Diplomat Eng., Ph D, Univ. Professor, PhD scientific advisor TRANSILVANIA U. of Brasov, Romania.

Abstract: *This paper work is part of a comprehensive research work comprising analysis of the assembly cylinder-piston-piston ring tribology aiming significant reduction of friction, wear, of fuel and oil consumption to minimize harmful emissions with highly efficient internal combustion engines. In-here presented paper work is dealing with the conformability of compression piston ring to the distorted cylinder liner to improve sealing performance and to reduce friction losses within the power cell unit.*

Keywords*: piston ring, conformability, cylinder liner/bore, gas pressure, friction, wear, oil consumption, particulate emission.*

1. INTRODUCTION

Worldwide environmental concern is leading internal combustion engines designs. International legislation is establishing milestones to achieve vehicle emission goals. To meet emission targets, main development directions are new exhaust gas after treatment, systems, combustion strategies and improvement of engine mechanical efficiency. When it comes to reduce engine friction power losses, the power cell unit, especially the piston rings pack, presents great potential. It is already well known that the cylinder-piston-piston rings assembly accounts for 37% of the engine friction loss; its perfecting could lead to a reduction of fuel consumption up to 5%.

The challenge to develop future power cell unit mainly consists of reducing friction power losses and weight while maintaining functionality of gas sealing, oil control and durability. This might require some compromise in component design and only a system approach (involving tribology, material science, simulation, testing, and manufacturing) together with a full understanding of interactions in the engine will lead to best decisions.

Many of the present and future intended major engine technological evolutions influence significantly the operating conditions of the power cell unit and have to be considered as additional constrains in the continuous efforts to reduce the friction power losses within the ring pack.

Engine downsizing and increased power density generate greater thermal and mechanical loads that require higher ring material and coating durability to stand increasing cylinder pressure. Higher thermal and mechanical loading means higher deformations of piston grooves and lands (especially on lightweight designs), as well as more important deformations of the cylinder bores (particularly of lightweight blocks with limited cooling capacities) needing better ring conformability.

Thus specific ring features are needed to guarantee the optimum management of gas and oil in the ring belt area to improve engine blow-by, reduce oil and fuel consumption, harmful emission, and ensure increased durability.

2. SOLUTIONS TO IMPROVE SEALING PERFORMANCE WITHIN THE PISTON RING-CYLINDER LINER CONTACT

2.1 Piston ring conformability to the distorted cylinder liner:

The ring capability to follow the shape and deformations of the cylinder liner is far from perfect. Conformability of the ring to the liner is proportional to the cylinder diameter, and influenced by the type of the block cooling and the displacement of the cylinder head assembling points.

Also depending on the position of the ring gap, the sealing is not along the entire circumference of the ring. Oil escaped through the ring gap during operation of the engine is significantly influencing the oil consumption and the amount of the particulate emissions.

For this reason, at the stage of engine designing, special attention has to be paid to the **thermal dilatations** of the elements of the cylinder-piston-piston rings couple at operating temperatures. The cylinder inner diameter, the outer diameters of piston and rings, the dilatation of piston grooves, and especially the ring gap clearance under thermal stress have to be considered. The **dynamic ring gap area** is 1.5…6 times the static ring gap clearance (the later one measured at room temperature) and is bigger at higher level of thermal stress, generating ring axial movement in its groove [7].

To obtain minimum oil consumption, the static gap between the cylinder liner and piston has to be designed to ensure minimum gap at operating temperatures.

2.2 Theoretical analysis of ring conformability considering reduced friction and improved sealing effect:

For a highly efficient engine design, it is of high importance an accurate prediction of tribological condition of the piston compression ring-cylinder liner contact in reversal through Top Dead Center (TDC), between 300° and 400° crank angle, which accounts for a significant portion of overall friction losses in engine cycle.

As in real situation, there exists a bore out-of-roundness, during piston ring-bore fitment this leaves a non-uniform gap between ring and bore because of which the minimum oil film varies in circumferential direction. A conformability analysis is required to estimate these irregularities in the liner-ring sliding contact to find best minimization solutions.

The minimum ring-bore gap is function of the ring geometry and tension, combustion gas pressure and bore shape.

To compute the radial deformation of a classical compression ring that is considered an incomplete circular ring, it is assumed that its deflection is the one of a curved beam fixed at the point opposite to the free end.

In an operating engine, is needed a balance of the lubrication reaction force with the resultant of the gas force and elastic pressure force. Imbalance decides the regime of lubrication and may lead even to metal-to–metal contact. For an accurate analysis, most suitable is a mixed lubrication model based on the average Reynolds equation and considering the double-honed liner inner surface roughness value into the pressure estimation [8].

The usual free end gap of the compression ring of 7…10 mm is reduced to 0.1 mm when fitted in situ.

Fig. 2.2.1 shows measurements of ring-liner conformability realized on a coordinate measuring machine.

Measurements of bore and outer ring radii (the doted lines) are made with an accuracy of 1.5 μm [8], the full lines being the mean of these radii. To represent the outer ring radius, its inner radius is measured in situ, and both of its inner and outer radii were initially measured in its free state, determining its variable depth. It was assumed that no significant deformation in the depth of the ring would occur during its fitment. Thus, its outer radii can be calculated at each circumferential position when fitted. The difference between the outer ring and the bore radii, χ, accounts for the gap between the deformed compressed ring and the out-of-round cylinder liner. This gap varies around the circumferential direction from nearly no gap tom approximately 10 µm, ring-bore conformance being asymmetrical as would be expected.

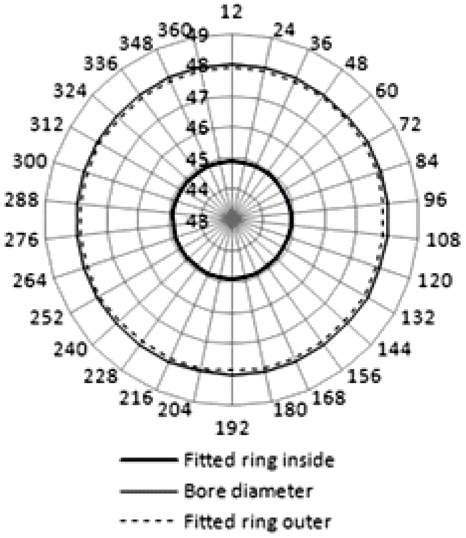

Fig. 2.2.1 Ring-bore conformability: fitted ring-bore gap

Conformability represents the ability of a ring to conform to the bore surface and it is function of gas pressure force (**Fg**), elastic pressure force (**Fe**), the ring and bore geometries and material properties.

Equation (1) shows the mathematical form of the **conformability factor**:

$$\xi_n = \frac{3\left(F_e + F_g\right) R_b^2 (2R_b - \kappa)^2}{2\pi E_r r_0 b \kappa^3 (n^2 - 1)^2} \qquad (1)$$

3. Chosen solutions to improve piston ring conformability to cylinder liner:

More uniform distribution of the pressure force and conformability may be achieved by new constructive solutions for the ring.

3.1 Magnetic piston ring:

Magnetic piston ring (**Fig. 2.2.1**) comprises a magnetic joint made of three sections of 120-degree arc, the radii of the three arcs being the same, as well as the magnetism at the contacted positions of the arcs [9]. This solution has the beneficial effects of a better bonding property between the magnetic ring and the cylinder sleeve and more uniform than that of an elastic single opening ring. Therefore, the cylinder sleeve is not easy subdued to an elliptical deformation. After a period of ring and cylinder liner wearing, the overlapped parts can automatically extend to fill the gap, and thus no leakage is taking place. Such a solution is improving the tightness, delaying the lubricating oil aging, prolonging the service life of the engine parts and is improving the efficiency of the engine in its whole.

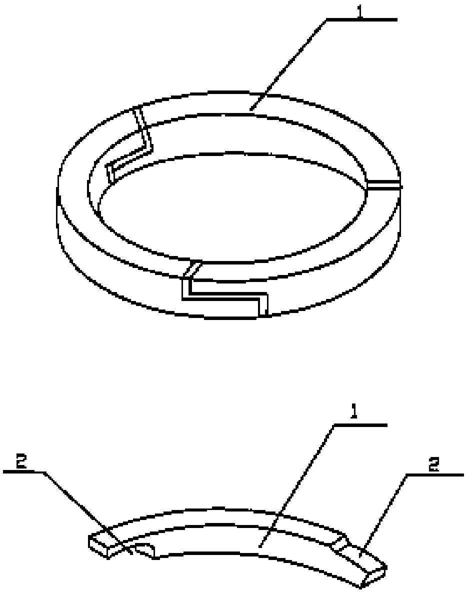

Fig. 3.1.1 Magnetic piston ring: **1** – section; **2** – joint

3.2 Asymmetrical complementary-close piston ring:

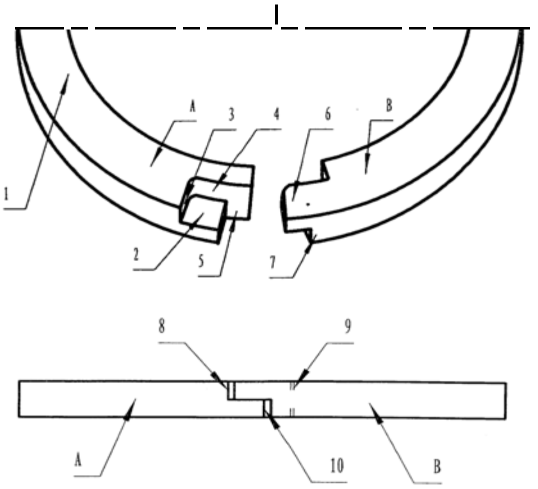

Fig. 3.2.1

End-unsymmetrical complementary close-type piston ring (**1**), including a concave semi-step (**2**), a concave semi-step upper side wall (**3**), an upper closure side wall (**4**), and a lower closure side wall (**5**) which are on the end (**A**) of one side of the piston ring, and a convex semi-step (**6**) and a semi-step (**7**) which are on the end (**B**) of the other side of the piston ring. **8**, **9** and **10** are designed dilatation gaps in the closed (mounted) state of the ring.

In mounted state, the ends of this type of compression ring are processed to realize a continuous chain of surfaces in contact, thus ensuring perfect sealing also at the ends of the ring [10].

The pressured gas inside the cylinder will no longer leak from the joint of the two ends of the notch of the piston ring during the compression stroke and working stroke of the internal combustion engine, meanwhile the piston ring will not clog due to the high temperature.

Furthermore, the sealing is improved and the operating time of the piston ring is increased, the heat evacuation rate is efficiently improved, and the output power of the internal combustion engine is increased.

This type of ring close is wear resistant; it automatically expands to compensate wear so that it ensures long-term stability of the engine power and reduced oil and fuel consumption.

3.3 Piston ring with variable geometry to conform perfectly to the cylinder liner shape:

To reduce friction and improve the sealing effect of the ring pack through better conformability of the compression ring to the cylinder liner, a solution is a piston ring having variable width along its circumference to compensate liner distortions [11]. In non-deformed state (before mounting), it has a circular outer circumference, and an inner non-circular circumference, the inertia momentum of its cross section being function of the cube of the ring width, **d**, for the respective section: **$M = f(d^3)$.** Ring flexibility is higher for lower width.

Conjugation of cylinder liner with deviations from circular shape (cross-section) with a ring having a circular outer circumference often gives important fluctuations of the radial pressure between the ring and liner along its circumference.

Under adverse operating conditions, peaks of radial pressure may alternate with lower values of the radial pressure causing significantly increased wear and even the apparition of a gap between the cylinder wall and the ring that will be increased by the gas force action, this worsening the sealing function of the ring.

To solve the gap by increasing ring pressure upon the liner is not acceptable because this is causing increasing of friction force and fuel consumption and lowers engine performance.

The ring with variable geometry is ensuring more uniform distribution of the radial pressure force acting between the ring and the liner. The radial pressure fluctuations have to be less than 20%, better within 10%.

Maximum designed flexibility of the ring is at its ends, to minimize radial pressure force peaks. Greater ring flexibility corresponds to the areas where liner has most important deformation, to ensure better conformability.

The ring is designed to comply with the specific cylinder liner distortions (pre-estimated), mounted on the designed position and indexed with the help of an anti-torsion system realized in piston (**Fig. 3.3.1, 3.3.2**). Such type of ring is designed in pair with the cylinder it will make a tribological couple. Variation of ring width along its circumference is of few tens of mm.

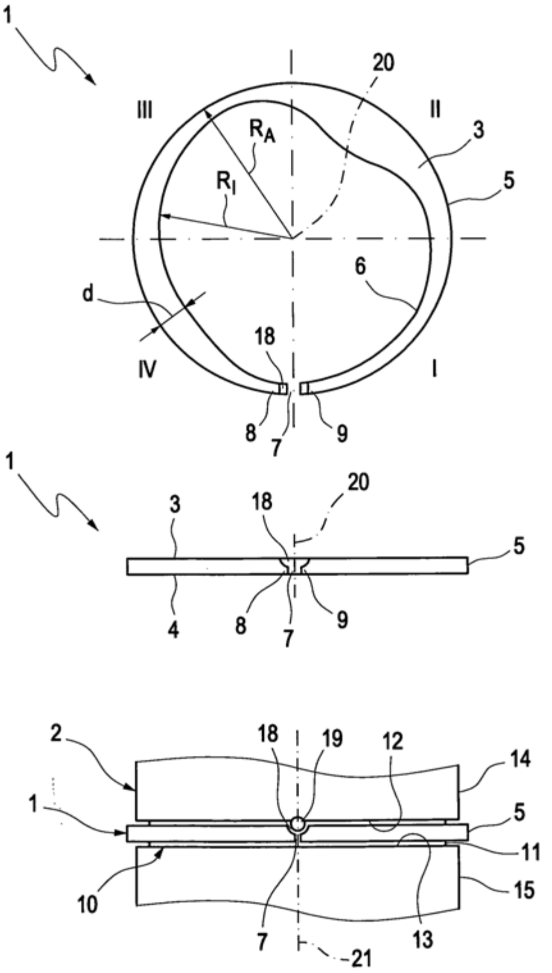

Fig. 3.3.1 Piston ring with variable geometry:
Top - schematic top view of a piston ring for a piston of an internal combustion engine in the un-deformed state (before mounting);
Middle - side view of the piston ring (before mounting);
Down - side view of the piston ring after insertion into a circumferential groove of the piston (mounted).

1 - piston ring;
2 - piston;
3 - upper side of the segment;
4 - lower side of the segment;
5 - circular outer circumference of the ring;
6 - inner non-circular circumference of the ring;
7 - gap at the ends of the segment;
8 and **9** - ends of the ring;
RA – radius of the outer circumference of the un-deformed ring (before mounting);
RI - distance from the ring axis to the inner non-circular circumference of the un-deformed ring;
10 - ring groove in piston;
11 - inner ring groove wall in piston;
12 - upper side of the ring groove in piston;
13 - lower side of the ring groove in piston;
14 - piston outer surface above the ring groove;
15 - piston outer surface under the ring groove;
17 - radial pressure of the deformed ring (mounted);
18 and **19** - ring anti-torsion system;
20 - ring axis.

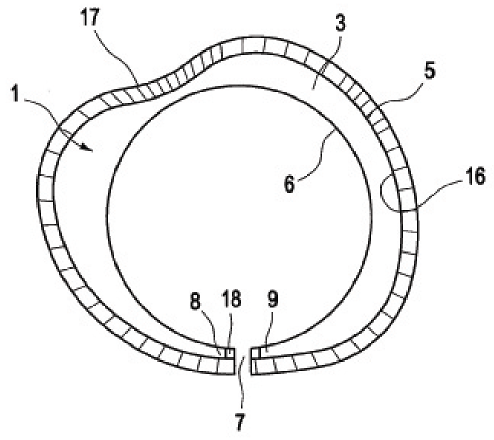

Fig. 3.3.2 Top view (schematic) of the deformed ring, mounted into its groove in piston, and radial pressure distribution along the ring-cylinder liner contact during engine operation.

1 - ring in deformed state;
3 - ring upper side;
5 - outer circumference of the ring;
6 - inner circumference of the ring;
8, **9** - ends of the ring;
16 - cylinder bore (deformed);
17 - radial pressure distribution;
18 - segment ends processed in the form of a circle arc, for anti-torsion mounting.

4. CONCLUSIONS

Friction, blow-by and blow-up, fuel and oil consumption and oil aging time through the power cell unit, and finally the whole engine durability and efficiency, are significantly influenced by the sealing performance of the rings pack determined, on its turn, by the compression ring capability to conform to the deformed cylinder liner.

Bore deformation is depending on the engine size, block type and its cooling capacity, on the block head mounting design, as well as on the temperature gradients in the cylinder during engine operation.

To improve piston ring conformability to the cylinder liner, new solutions have to be chosen to ensure adequate sealing effect.

Maximizing compression ring conformability will lead to reduced friction, wear, oil and fuel consumption and higher durability of the power cell unit and will contribute significantly to achieve the emission targets with a modern engine. It gas to be applied together with the other technical solutions to improve the tribological behavior of the cylinder-piston-piston rings system such as: perfecting the liner and ring surfaces in sliding contact regarding shape, material, texturing, coating, finishing ([1], [4], [5], [6]).

The main author of in-here presented research work intends (within her PhD studies) to continue the optimization process of the cylinder liner and especially of top piston compression ring to meet the main goals of this research: minimizing the frictional losses, wear, oil and fuel consumption, as well as the particulate harmful emissions with high performance internal combustion engines.

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