

## **Tribological Principles of Constructing the Reciprocating Machines**

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### ABSTRACT

*Reducing vehicle weight contributes to reducing fuel consumption and exhaust emissions. In practice, this is achieved by application of lightweight materials and through optimization of tribo-systems on the vehicle. The benefit of using aluminium is evident due to the reduced mass of the parts, but in parallel there is a problem due to the low strength of this metal. This is especially evident during overheating when can form cracks. The wear resistance and tribo-properties of aluminium are the problem, too. To achieve the strength and tribo-properties of aluminium alloys similar to grey cast iron, we applied eco-tribological knowledge during construction of reciprocating machines. The result of researches is patented prototype of aluminium piston and cylinder whose contact surfaces are coated or modified with inserts based on the tribo-materials.*

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## **1. INTRODUCTION**

The EU has set out an ambitious strategy to reduce CO<sub>2</sub> emissions from road vehicles. According to European Commission Directive 93/116/EC, total CO<sub>2</sub> output in Europe must aim to reach an average of 130 g·km<sup>-1</sup> for all new passenger cars by 2015 and 95 g·km<sup>-1</sup> by 2020 [1]. At the same time, the use of lower viscosity lubrication oil and other measures for the reduction of fuel consumption such as start/stop systems, downsizing of engines and engine components as well as high-pressure turbo injection technologies, are leading to higher loads and increased wear. As a result, by modifying the surface of components in the powertrain by reducing friction and increasing

wear resistance, engine coatings look set to play an increasingly important role in improving fuel economy, reducing CO<sub>2</sub> emissions and meeting those tough legislative targets.

In passenger cars, one-third of the fuel energy is used to overcome friction in the engine, transmission, tires, and brakes. The direct frictional losses, with braking friction excluded, are 28 % of the fuel energy. In total, 21.5 % of the fuel energy is used to move the car. By taking advantage of new technology for friction reduction in passenger cars, friction losses could be reduced by 18 % in the short term (5–10 years) and by 61 % in the long term (15–25 years). This would equal worldwide economic savings of 174,000 million euros and 576,000

million euros, respectively; fuel savings of 117,000 million and 385,000 million liters, respectively; and CO<sub>2</sub> emission reduction of 290 million and 960 million tones, respectively [2].

Potential actions to reduce friction in passenger cars include the use of advanced coatings and surface texturing technology on engine and transmission components, new low-viscosity and low-shear lubricants and additives, and tire designs that reduce rolling friction. Generally, coatings are needed to improve wear resistance and friction reduction at higher loading densities, higher temperatures and with lower viscosity oils.

In accordance with previously set goals, we have realized the research in the field of optimal design of reciprocating aluminium engines and compressors. Consequently, we investigated new option for increasing strength and tribological characteristics of the tribo-system piston-cylinder liner.

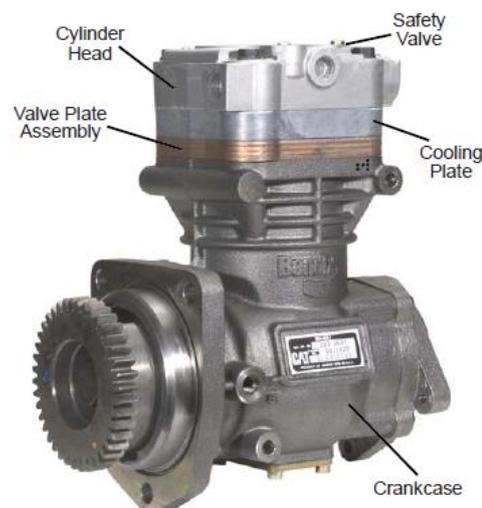
The result of researches is patented prototype of aluminium piston and cylinder whose contact surfaces are coated or modified with inserts based on the tribo-materials.

## 2. PERFORMANCE OF RECIPROCATING COMPRESSORS FOR AIR BRAKE SYSTEM

Within a pneumatic braking system of buses, trucks and tractors, reciprocating compressor is driven by an internal combustion engine and operates at different speeds (from 1000 to 3000 rpm). In doing so, the pressure in the brake system is regulating by means of relief valve. The compressor compresses the ambient air to a pressure of about 0.6 to 0.8 MPa and stored it in cylinders on the vehicle. In reference [4,5], it was shown that the air temperature at exhaust of the compressor can achieve up to 400 °C, but using the cooling system on the vehicle, the temperature is maintained at about 250 °C. To avoid premature damage, air compressors made of aluminium alloy, have a maximum projected temperature limited to 200 °C [3,4].

As example, a typical design of the reciprocating compressors which used to compressing the air of brake systems in commercial vehicles, shown is in Fig. 1 [5]. The compressor has a combined

cooling of the cylinder and the cylinder cover (cylinder head).

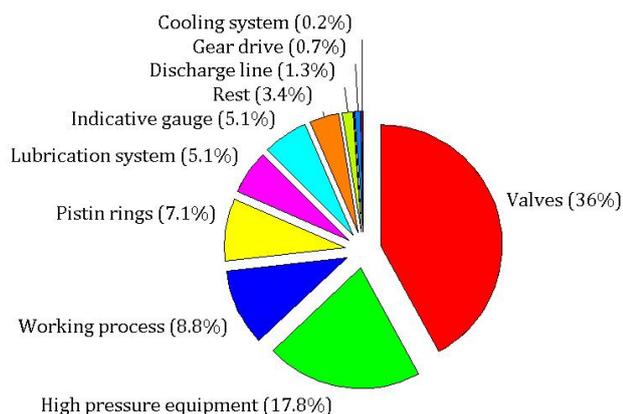


**Fig. 1.** Air reciprocating brake compressor BENDIX® BA-921®.

Loading cycle of reciprocating compressors is defined as the ratio between the active delivery time of compressed air for the brake systems operation, and the total working time of drive engine. Air compressors are designed for a maximum of 25 % of work under load [5]. Extended work under load regime can damage the compressor, causing poorly performances of braking system. The latter is usually consequence of additional use of compressed air for the operation of the vehicle systems (suspension, activation of auxiliary devices and equipment, etc.), installation of compressor whose capacity is lower than required, frequent use of the brake system, leaking in the system, etc.

In case of overload due to excessive mechanical and thermal loads, compressors, mostly break down due to loss of functionality valves, Fig. 2 [6]. Poor sealing valve and leakage of compressed air inside the compressor cylinder causing a pressure drop in the brake system of the vehicle, as well as overheating and fatigue of the compressor.

Compressor valves are identified as the primary causes (36 %) break down of reciprocating compressors, Fig. 2 [6]. This figure only shows the reliability of an operating compressor. Other causes of failure of reciprocating compressors are pressurized equipment, piston rings (7.1 %), the poor quality of lubricating oil, obstruction inside of the air supply lines, etc.



**Fig. 2.** Reasons for non-scheduled failures of the reciprocating compressors.

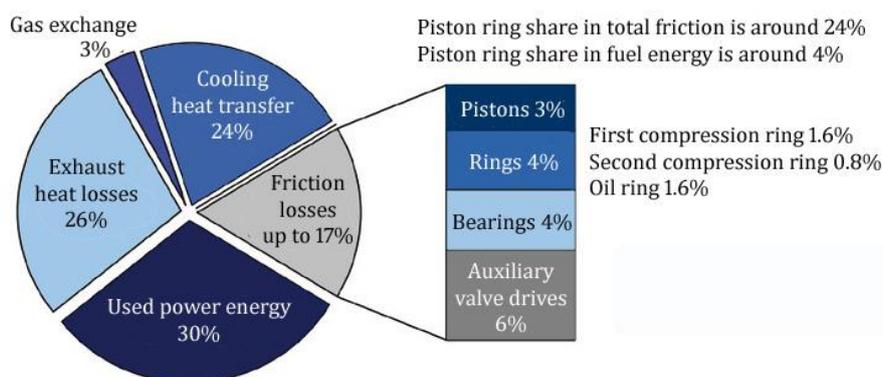
Current trucks and buses airbrake systems simply dump excess pressure to ambient when the air tanks are full, the compressor keeps running. For long-haul trucks and coaches work, the airbrake system may not be used for up to 90 % of the time. Otherwise, in the case of city buses where has been intensively used the compressed air for braking and the work of auxiliary systems, the compressor is constantly under load.

Applying the method for deactivation of reciprocating compressor we can affect the reduction of parasitic losses due to engine overload caused by the reciprocating compressors within the braking system of trucks and buses. The compressor would be operated in that case only during of braking and idling, which is not the case within the conventional constructions. Deactivation of the compressor is applicable technology with integrated electric/air actuated clutch. With deactivating of the compressor if there is no consumption of compressed air in systems the vehicle, can be achieved the reducing of CO<sub>2</sub> emissions by around 6 % in the case of coaches, or 1.5 % for a truck-tractor [7].

### 3. TRIBOLOGICAL RESEARCH

Tribology has supported various technological developments over the years, such as improving the energy efficiency and durability of vehicles, household appliances, industrial machines and plants. Tribology has also responded promptly to societal demands for decreasing substances from engineering products that would be hazardous to the environment, which has included abolishing asbestos from vehicle brake systems, replacing refrigerants with CFC-substitutes, and controlling the lead used in bearings [8].

Manufacturers of reciprocating engines and compressors continuously working on introduction of measures which leading to increase effectiveness of working processes by reducing the mechanical losses caused due to the friction force. Parts of piston group, cylinder and crankshaft are in the focus of all research. For example, by optimizing the material of piston rings largely we can reduce friction losses. The reason for this is the high share of piston rings (24 %) in the overall mechanical losses, due to friction forces in the engine. According to the latter, it should be recalled on the situation concerning the losses in the engine. Thus, for example, in case of the gasoline engine of the total energy that is obtained by fuel combustion, only 30 % is used at the flywheel, while the rest goes to the losses, Fig. 3. Of these losses, 3 % goes to the gas exchange, 17 % on the friction losses, 24 % on heat transfer during cooling and 26 % is lost during exhaust process. Losses of friction are distributed in the following percentages: 3 % pistons, 4 % piston rings as well as bearings and 6 % on the auxiliary the drive system of valve [9,10].



**Fig. 3.** Energy distribution diagram showing friction losses in gasoline engines with the proportionate share of the piston rings.

Lowering engine friction can improve CO<sub>2</sub> emissions. Similar is valid for accessories (airbrake compressor). This mind about reduction in reciprocating machine friction with improvements in piston, piston ring and cylinder liner package as well as crankshaft system in design and surface finish. Simultaneously, into the application are the engine oils with lower viscosity and appropriate additives to reduce friction.

Reducing friction in reciprocating machines can be achieved by using appropriate materials and optimizing the structure of the piston and piston group. Tribo-logical materials and coatings are one of the options for increasing strength of the aluminium parts of reciprocating engines and compressors. Their application contributes to the reduction of friction and wear, which are more intensive in the working conditions under the high temperature and loads, as well as through use of lubricating oils lower viscosity [11-13]. The right choice of engine oil specifications is of great importance and can contribute to reducing the friction of propulsion system. From the oil is expected to have a lower viscosity, to provide extended drain intervals that are enriched with additives such as modifiers of friction and anti-wear and anti-oxidizing agents that are environmentally neutral.

The fact is, for example, that the available types of reciprocating compressors for production of compressed air to the motor vehicles have a classic design, usually made of grey cast iron. Increasing vehicle efficiency through weight reduction is the goal of every designer of the vehicle. This is the main reason for the replacement of steel parts with aluminum.

Aluminum parts, on the one hand include the large amount of energy as well as the resources needed for manufacturing. On the other hand, the use of aluminum components contributes to a reduction in fuel consumption due to reduced mass of the vehicle. The benefit of using aluminium is evident due to the reduced mass of the parts, but in parallel there is a problem due to the low strength of this metal. This is especially evident during overheating when can form cracks. In that case, due to increased gap inside tribo-logical system between the piston, piston rings and cylinder liner, the lubricant flowing from the housing in direction of the cylinder via exhaust line. The combustion of

lubricants in the overheated air inside of cylinder contributes the forming of particles. Soot particles are the main cause blockage of the supply line of reciprocating compressors, and hence the failures function of the brake system of the vehicle. On the other hand, inside IC engines, the presence of soot in exhaust system leads to an increase of exhaust emissions.

The wear resistance and tribo-properties of aluminium are the problem, too. To achieve the strength and tribo-properties of aluminium alloys similar to grey cast iron, we applied eco-tribo-logical knowledge during construction of reciprocating machines.

We investigated inside of the paper, the implementation of tribo-logical principles for construction of reciprocating machines. For this purpose it was used sample of patent piston and cylinder of aluminium alloy. Since aluminium alloy has low resistance to wear, i.e. poor tribo-logical properties [12], the inner surface of the cylinder is reinforced by applying a coating of tribo-materials by using plasma technology in atmospheric conditions. In the second case, on the thus prepared inner surface of the cylinder inserted are the tribo-logical inclusions of graphite in the form of continually placed lamella/plates and/or in form of discrete tribo-logical inclusions, balls/nodes. For the purpose of research it was designed and patented the piston with tribo-logical pads on skirt side, too [12].

#### **4. NEW CONCEPT OF TRIBO MECHANICAL SYSTEM PISTON AND CYLINDER**

We have started the laboratory testing of a patented small experimental reciprocating air compressor, which is made of aluminium alloy, the ratio of bore/stroke (74/35 mm·mm<sup>-1</sup>). The main compressor, before reconstruction it was constructed of grey cast iron. For purposes of testing the performance of the reciprocating compressors, we projected the installation for measuring in the Laboratory for IC Engines at the Faculty of Engineering University of Kragujevac (FINKG) [4,12].

With the aim to achieving strength as well as tribo-logical characteristics similarly as in case of the application grey cast iron, we patented the

aluminium cylinder for reciprocating air compressor with the inserts consisting of tribo-logical materials.

On the inner surface of the cylinder, whose base alloy ALSi (EN ALSi10Mg), in first case were inflicted the coatings in the form of powder by means of plasma spray process under atmospheric condition. Coating material (cast iron) is resistant to wear and has high mechanical strength and tribo-logical characteristics, Fig. 4 [12,13].



**Fig. 4.** Photography of cylinders coated inside by Rotaplasma® process before experiments.

In the second case, Fig. 5, the internal surface of the cylinder (1), which is in constant contact with the parts of the piston groups was coated by putting tribo-logical inserts of graphite that are arranged in the form of continuous pads, the plates (2) and/or like discrete tribo-logical plugs in the form of spheres (nodule), spherical shape (3) [12].

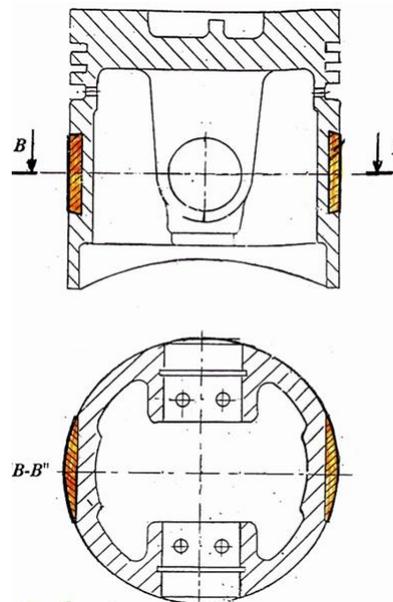


**Fig. 5.** Cross section of patented aluminium cylinder (1) with tribological pads (2-continual and 3-nodular discrete pads).

The aim was that the surface of the cylinder additionally strengthens mechanically by means of continuously deployed inserts of graphite, in form of plate or as nodular graphite. It is known that graphite as a solid lubricant can improve the tribo-logical characteristics of the material

because of increasing wear resistance. This is especially important to know when optimize tribo-mechanical systems where exists a problem with regard to lubrication. Such systems include here analysed assembly of the piston group that is in constant contact with the cylinder liner in a well-known conditions, be it inside of reciprocating IC Engine or compressor.

Starting from the fact that each the optimization in terms of tribology has a theoretical basis, i.e. to ensure conditions when the boundary lubrication continuing to be hydrodynamic, we designed and patented the piston with tribo-logical pads. Tribo-logical pads are mounted opposite each other on part of piston skirts. This solution is applicable for reciprocating IC engines, Fig. 6, as well as inside the reciprocating compressors [12].



**Fig. 6.** Cross section of patented aluminium piston with tribological pads.

The task of tribological inserts which are integrated into the new solution of piston design, is to contribute to the reduction of losses due to friction within the tribo-mechanical system piston and cylinder, especially during of the cold start of the machine.

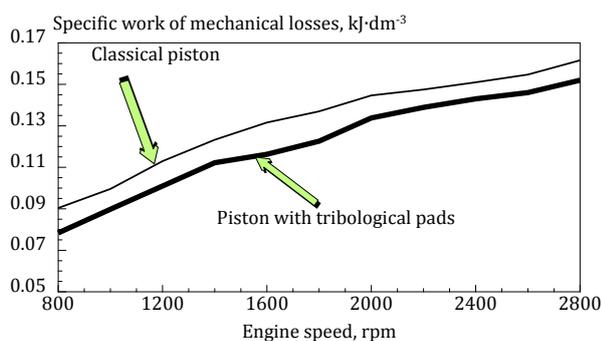
Applying of invention of the piston with tribological pads, resolved is the problem of wear through replacement of easily removable pads. From the aspect of vehicle exploitation, maintenance of the piston in the future will be related to the replacement of easily removable piston rings and pads during service. In these

conditions, the piston is viewed as a carrier of easily interchangeable parts.

## 5. EXPERIMENTAL RESEARCH

The first experiments were carried out by researchers at FINKG on the experimental IC engine (Type: 3LD450, Maker: DMB Lombardini, four-stroke, single-cylinder, and air cooled). Basic characteristics of the engine and equipment have been published in the paper, of the authors prof. R. Pešić with assistants [12,14].

Figure 7 shows the comparison of values relating to the specific effective work of mechanical losses experimental IC engine during working with conventional piston made of cast iron, as well as with aluminium piston with tribo-logical inserts. Measurement was performed in laboratory conditions, on the IC engine without burning, with electric motor drive, by applying method of disassembling/eliminating of its parts. First, is dismantled the cylinder head in order to determine the forces of resistance in the cylinder, and then piston rings respectively, and at the end the piston and piston rod. Any time during the change, were performed the measurement of torque so that difference presents share of dismantled part in the total losses.



**Fig. 7.** Specific work of mechanical losses vs. engine motoring speed.

By analysing the results it can be confirmed the aim with regard to the application of piston with tribo-logical pads, i.e. it is confirmed the reduction of friction within tribo-mechanical systems piston-cylinder.

Further research is aimed at determining of tribo-logical characteristics of new conception of piston and cylinder for reciprocating air compressors in

conditions of sliding (intensity of wear...). Investigation the performance of optimized experimental compressor should contribute in the selection of the best conceptions.

## 6. CONCLUSIONS

Vehicles are demands to meet stringent regulations for emissions of toxic and harmful products of combustion. In the European Commission Directive 93/116/EC prescribing an average value for passenger cars produced after 2015 CO<sub>2</sub> emission 130 g·km<sup>-1</sup> and 95 g·km<sup>-1</sup> after 2020.

Coatings of the tribo-materials on contact surfaces between the parts of drive system contribute to reducing friction while increasing resistance to abrasion. The latter contributes to reducing fuel consumption that has a direct impact on reducing CO<sub>2</sub> emissions.

With the aim to achieving strength as well as tribo-logical characteristics similarly as in case of the application grey cast iron, we patented the aluminium cylinder for reciprocating air compressor with the inserts consisting of tribo-logical materials. We designed and patented the piston with tribo-logical pads. Tribo-logical pads are mounted opposite each other on part of piston skirts. This solution is applicable for reciprocating IC engines.

By analysing the results it is confirmed the aim with regard to the application of piston with tribo-logical pads, i.e. it is confirmed the reduction of friction within tribo-mechanical systems piston-cylinder liner.

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## REFERENCES

- [1] Cars, *Greenhouse Gas Emissions*, available at: <https://www.dieselnet.com/standards/eu/ghg.php>, accessed: 03.02.2015.

- [2] K. Holmberg, P. Andersson and A. Erdemir, 'Global energy consumption due to friction in passenger cars', *Tribology International*, Vol. 47, pp. 221-234, 2002.
- [3] O. Bielmeiler and T. Mullner, *Treatment on Heat Transfer in Small Piston Compressors*, available at: [http://publik.tuwien.ac.at/files/PubDat\\_182892.pdf](http://publik.tuwien.ac.at/files/PubDat_182892.pdf).
- [4] D. Taranović, 'The test bench for non-standard testing of reciprocating compressors for motor vehicles', Ph.D. thesis, Faculty of Engineering, University of Kragujevac, Kragujevac, 2013.
- [5] Air Compressors, *Advanced Troubleshooting Guide for Air Brake Compressors*, available at: [http://www.bendix.com/en/servicessupport/documentlibrary/doclib\\_1.jsp](http://www.bendix.com/en/servicessupport/documentlibrary/doclib_1.jsp).
- [6] R.A. Habing, 'Flow and Plate Motion in Compressor Valves', PhD thesis, University Twente, 2006.
- [7] H. Baker, R. Cornwell, E. Koehler and J. Patterson, *Review of Low Carbon Technologies for Heavy Goods Vehicles*, Ricardo UK, 2009.
- [8] S. Sasaki, 'Environmentally friendly tribology (Eco-tribology)', *Int. J. Mech. Science and Technology*, vol. 24, no. 1, pp. 67-71, 2010.
- [9] M. Kennedy, S. Hoppe and J. Esser, 'Piston ring coating reduces gasoline engine friction', *MTZ Motortechnische Zeitschrift*, vol. 73, no. 5, pp. 40-43, 2012.
- [10] P.C. Mishra, 'Modeling for Friction of Four Stroke Four Cylinder In-Line Petrol Engine', *Tribology in Industry*, vol. 35, no. 3, pp. 237-243, 2013.
- [11] S. Mitrović, M. Babić, B. Stojanović, N. Miloradović, M. Pantić, D. Džunić, 'Tribological Potential of Hybrid Composites Based on Zinc and Aluminium Alloys Reinforced with SiC and Graphite Particles', *Tribology in Industry*, vol. 34, no. 4, pp. 177-185, 2012.
- [12] R. Pešić, *ASMATA-Automobile Steel Material Parts Substitution with Aluminum*, Int. J. Vehicle Mech., Engines and Transportation Syst., Faculty of Mechanical Engineering, University of Kragujevac, 2004.
- [13] A. Vencl, 'Optimization of the Deposition Parameters of Thick Atmospheric Plasma Spray Coatings', *J. Balkan Tribological Association*, vol. 18, no. 3, pp. 405-414, 2012.
- [14] R. Pesic and S. Milojevic, 'Efficiency and Ecological Characteristics of a VCR Diesel Engine', *Int. J. Automotive Technology*, vol. 14, no. 5, pp. 675-681, 2013.