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Machinery breakdown – preventive maintenance

TRIBOLOGICAL OPTIMISATION OF RECIPROCATING MACHINES ACCORDING TO IMPROVING PERFORMANCE

S. MILOJEVIC*, R. PESIC, D. TARANOVIC

Faculty of Engineering, University of Kragujevac, 6 Sestre Janjic Street, 34 000 Kragujevac, Republic of Serbia
E-mail: *tiv@kg.ac.rs*

ABSTRACT

Lowering fuel consumption and exhaust emissions continue to be prime targets in the development of technology applied for motor vehicles and their equipment. Into the focus of attention are the reduction of the vehicle weight as well as, in the field of internal combustion engine technology, more efficient combustion system and accessory components.

As a complex system, the internal combustion engine accounts for a major part of the vehicle mass. The key components, the cylinder head and the cylinder block, for heavy loaded diesel engines, are today almost exclusively produced from aluminum. Also, by application of the aluminum pistons, it reduces engines weight and inertial forces, as well as the engine vibrations. According to the latter, the use of lightweight materials for construction of engine accessories as it is small air reciprocating compressor for braking system of trucks and buses, give contributions to the reduction of equipped vehicle mass.

The advantage of aluminum with regard to the specific weight is notable, but exist the problem because it has considerable disadvantages in terms of the thermal expansion coefficient. The greater thermal expansion would cause unacceptable deformation during reciprocating machine operations. With additional coating on the cylinder liner surfaces it overcomes poor aluminum strain properties. By application of piston with tribological inserts towards lowering friction resulting in lower mechanical losses and higher performance. The authors hope to obtain more measurement data on the test bench for small air reciprocating compressors in the Engine Laboratory at the Faculty of Engineering, University of Kragujevac.

Keywords: reciprocating aluminum machines, coating, lowering friction.

* For correspondence.

AIMS AND BACKGROUND

Society relies on reciprocating machines for transportation, commerce and power generation. Today, Internal Combustion Engines (ICEs) power the world fleet of vehicles, which passed one billion passenger cars and other vehicles on our roads.

In gasoline-powered vehicles, over 62% of the fuel energy is lost in the ICEs. ICEs are very inefficient at converting the fuel chemical energy to mechanical work, losing energy to engine friction, pumping air into and out of the engine, and wasted heat[1,2]. Advanced engine technologies such as variable valve timing, turbocharging, direct fuel injection, and cylinder deactivation can be used to reduce these losses.

The popularity of diesel engines in passenger cars is the result of their economy and improved drive ability in recent years. Diesel engines are about 30–35% more efficient than gasoline engines. Diesel engines necessitate high peak cylinder pressure to ensure an appropriate torque and performance, together with low consumption and improved exhaust gas emissions. Moreover, an additional reduction of engine weight is required. Lightweight design has two goals: Fuel economy due to a lighter vehicle, on the one hand, and weight distribution in the vehicle (driving dynamics), on the other hand. Generally, diesel motorisation constitutes the heaviest assembly (robust construction, turbo charger, charge air cooler, fuel-injection equipment), so that the balance gets affected by the excess weight on the front axle[3,4].

At the core of these conflicting goals are the heaviest single components of the engine, the engine block and engine accessories (water pump, alternator, fans, air reciprocating compressor, etc.).

The aim of this paper was to analyse the application of lightweight materials in the design and manufacture of reciprocating machines as well as to analyse possible solutions to increase resistance to wear and friction reduction particularly the pistons and cylinders made of aluminum alloys. This paper aims also to present some original solutions in the design of the piston and cylinder made of aluminum which meet the previous requirements and to present one analysis as introduction to the experimental investigation resulting in optimisation of air reciprocating compressors as a contribution to reduction in parasitic losses in the reciprocating machines.

TRIBOLOGICAL METHODS IN CONSTRUCTION OF RECIPROCATING MACHINES

The main parameters which the designers need to know are friction, wear and service life of the machine parts. The use of AlSi (Alusil®) alloys as a substitution for engine cylinder block made of grey cast iron, in addition to positive aspects such as the lowering of engine weight has also negative tribology side if looking to undesirable properties of this material. According to the latter, need to be improved wear resistance of the aluminum alloys to provide their tribology similar to grey cast iron[3,4].

Today, a wide range of surface coating technologies is available and there are many different wear-resistant materials or material combinations which are applicable for surface coating[5–7]. Consequently, more of the methods have been examined or actually applied for the surface coating of aluminum cylinder liners.

Applying a coating directly to the cylinder surfaces in aluminum machine blocks can eliminate the need for cast iron sleeves. This can significantly reduce the weight of the block; leads to improved heat transfer from the combustion chamber into the water jacket and can give an extra corrosion protection of the running surface. One of existing solutions to overcome undesirable aluminum tribology is the direct coating of cylinder running surfaces with different technologies, among which the application of thermal spray process – plasma coating (Rotaplasma®) (atmospheric plasma spraying – APS) is often used. The whole process of the cylinder surface coating is illustrated schematically in Fig. 1 *a* on an aluminum engine block (without washing /cleaning). The process flow is identical for coating of liners that are typically made of cast iron. As indicated above, the APS coatings are applied with a rotating plasma torch designed for machine blocks (Fig. 1 *b*) (Ref. 5).

The atmospheric plasma spray process can apply by far the widest variety of coating materials of any thermal spray process. The flexibility of the plasma spray process is based on its ability to develop sufficient energy to melt almost any coating feedstock material in powder form. The feedstock material is injected into the

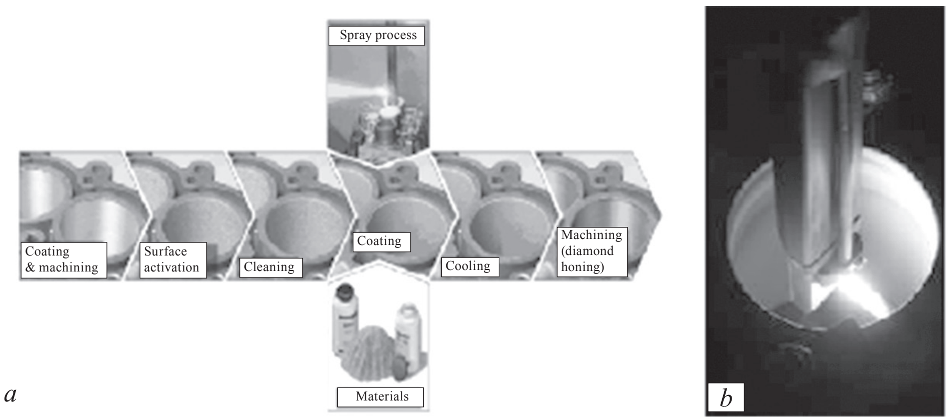


Fig. 1. Schematic representation of the SUMEBore coating process (from left to right, including honing)[5] (*a*) and F210 plasma torch in an ∅81 mm bore of an aluminum engine/gas compressor block[5] (*b*)

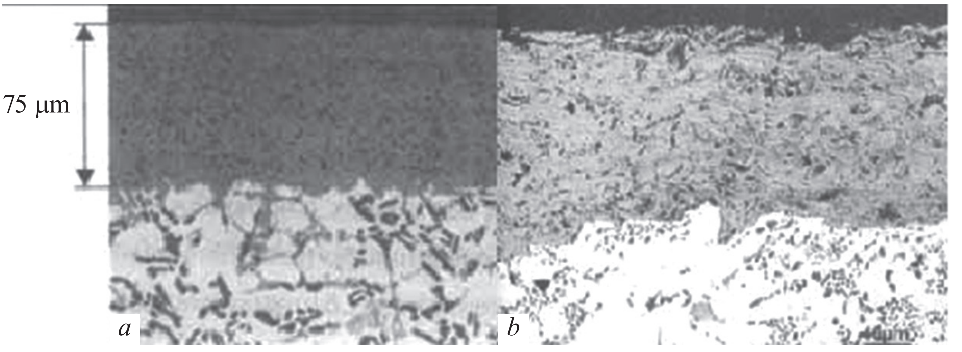


Fig. 2. Micrographs showing Ni-SiC dispersion layer (Kolbenschmidt)[6] (*a*) and plasma coating layer (Sulzer Metco)[6] (*b*)

hot plasma plume, where it is melted and propelled towards the target substrate to form the coating[5–8].

The composition of the coatings is dependent of the working conditions, as it is excessive abrasive wear, scuffing, corrosion caused by fuel and gases, intensified heat transfer from the combustion chamber into the water jacket, etc. The coatings must meet the requirements of intensive thermal stresses and wear resistance. Otherwise, the result could be delamination of coating materials and machine failures. Good results were achieved using Fe as a coating material. Furthermore, FeO and Fe_3O_4 can be dispersed in the layer acting as a solid lubricant such as graphite in grey iron (Fig. 2) (Ref. 6).

Piston rings coating – an example of tribological optimisation. Other applicable methods include laser coating of an AlSi alloy, physical (PVD) and chemical vapour deposition (CVD), etc., using materials such as diamond-like carbon (DLC), chromium nitride, titanium nitride, i.e. many different surface coating structures and chemistries.

The piston ring pack as example has a significant potential for bringing down friction losses due to its fairly high (24%) share of mechanical frictional losses in gasoline engines (Fig. 3). At the same time measures such as direct injection and turbocharging among others, which increase engine performance, intensify the requirements for the functional behaviour of piston rings[2].

When considering measures to optimise the tribology of the system piston ring and cylinder surface, piston ring coatings play an increasingly important role as they can directly influence the wear and friction behaviour and the resulting scuff resistance. By introducing Carboglide Federal-Mogul is providing a coating for piston ring applications which meets the most stringent requirements for functional behaviour and offers a considerable potential to reduce frictional losses[2].

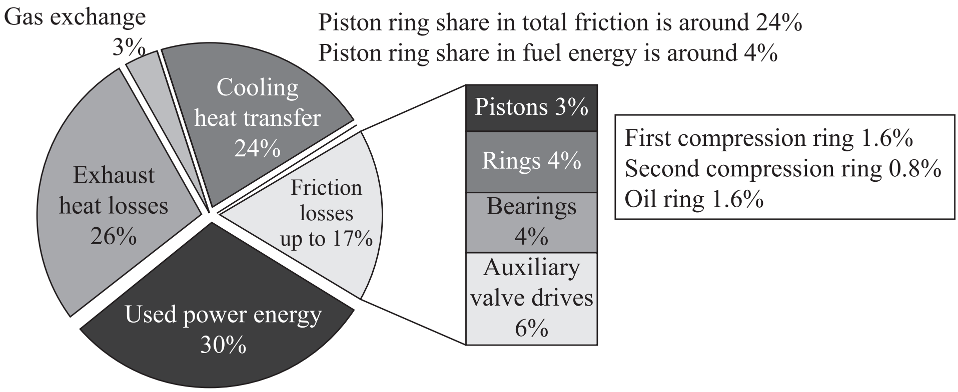


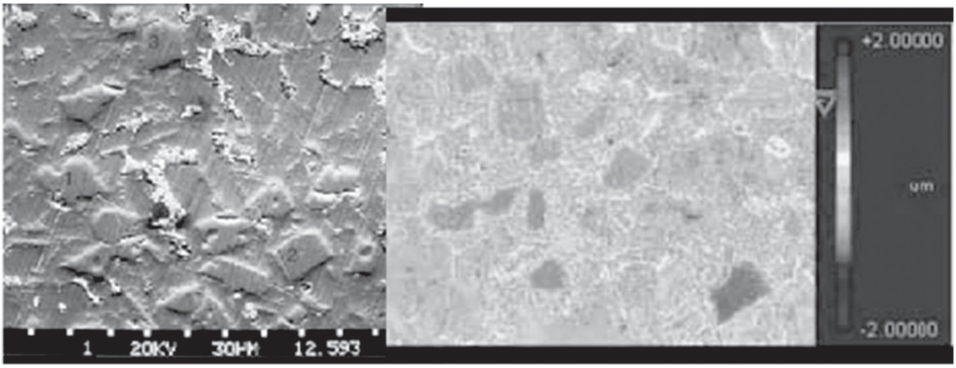
Fig. 3. Energy distribution diagram showing friction losses in gasoline engines with the proportionate share of the piston rings[2]

Carbon-based coatings (DLC, Diamond-like Carbon) have a long track record in applications for cutting tools and components that are tailored for the most severe tribological requirements[7].

The new coating combines extremely low friction values with high strength and durability of piston rings and cylinder running surfaces. By using this coating, the ring pack frictional losses can be reduced by up to 20%. It significantly protects the cylinder running surface against scoring, increased wear and scuffing during inadequate lubrication. Carboglide makes a substantial contribution to the development of high performance gasoline engines with even better fuel economy by up to 1.5% with consequently lowering exhaust emissions[2].

Honing of AlSi surfaces. The various cylinder liner manufacturing technologies based on hypereutectic AlSi alloy compositions (Alusil®, Silitecl®, etc.) rely on the presence of a dense distribution of hard, primary silicon particles which act as the tribological partners for piston and piston rings. The technical requirements like low friction, high stability and good lubrication under dry sliding conditions can only be met by the presence of an appropriate surface topography. This structure is created by a special honing process which is different from the conventional honing of grey cast iron. Honing of hypereutectic AlSi surfaces usually requires the following steps[6]:

- A pre-honing step corrects the cylinder shape and removes most of the damaged surface layer resulting from pre-machining.
- In the following base-honing step, the final surface shape of the primary silicon particles is created.
- Subsequently, a recessing of the Al matrix and an exposure of the Si particles is carried out providing both hard particles to withstand the sliding wear of the piston and to provide oil reservoirs for good distribution of the lubricant. For



a *b*

Fig. 4. Micrograph showing the final surface after honing with recessed Al matrix and exposed Si particles[6] (*a*) and image from white light interference microscope showing the topography of the final cylinder surface[6] (*b*)

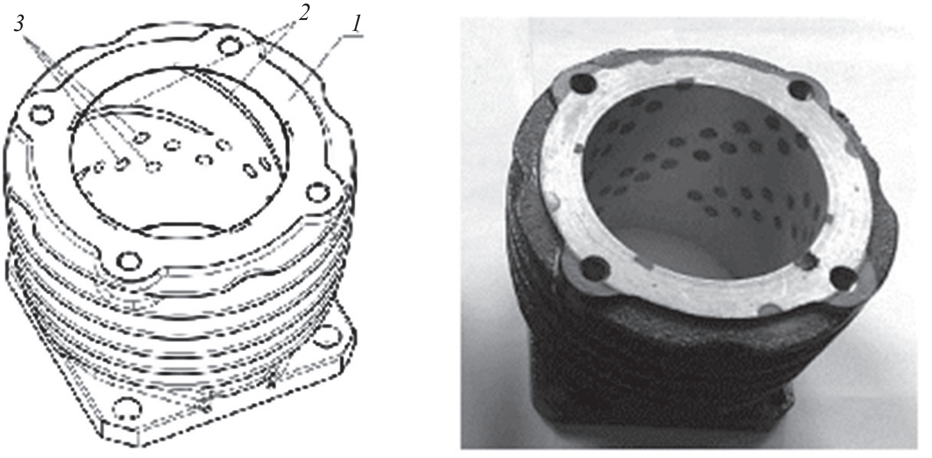
this honing step special tools are used with the abrasive particles being smaller than the Si particles and embedded in a soft matrix.

Compared to recessing by etching, this technique provides smooth particle edges which prevent break-outs (Fig. 4) (Ref. 6).

The new concept of piston and cylinder. In order to illustrate some of the concepts discussed above, patented is a small air reciprocating compressor with a 74 mm bore and 35 mm stroke with parts made from aluminum alloys. The previous was traditionally made from grey cast iron. The compressor is currently experimentally investigated on a custom test bench for small air compressors in the Engine Laboratory of the Faculty of Engineering, University of Kragujevac (FINKG)[1,9,10].

Use of Al alloys as a substitution for reciprocating machine blocks made of grey cast iron, has positive aspects in term such as reduction of machine weight, etc., as it is described above. If we are looking generally, most aluminum alloys, specifically those suitable for mass production from the technological and economic aspect, do not have satisfactory strength and wear resistance, i.e. their mechanical and tribological properties are relatively poor. According to this, the surface engineering of the engine cylinder liner is in the focus of most producers of aluminum reciprocating machines[1,5].

As a contribution, patented is the Al cylinder for experimental reciprocating air compressor with tribological inserts or coated inside by air plasma spray process (APS). Applied inserted or coating materials have good resistance to wear (appropriate steel or cast iron) and good mechanical and tribological properties. The continual tribological inserts (*2*) and/or discrete tribological inserts (*3*) are set into a cylinder (*1*) in the part over which piston rings slide during operation (Fig. 5) (Refs 1, 11). These methods are applicable specifically to improve tribo-



a *b*

Fig. 5. Draw of patented aluminum cylinder with tribological inserts (*2* – continual and *3* – discrete inserts)[1,11] (*a*) and photo of patented aluminum cylinder with discrete tribological inserts[1,11] (*b*)

logical characteristics of Al alloys. The main idea is that relatively small amount of reinforcement can improve characteristics of material by several time. Also, the fact is that tribological properties define possible application of material, far more than their mechanical properties, since they are in better correlation with behaviour in practice.

However, more measurement data are required before a fully qualified statement as to its general utility can be made. There are a great number of parameters that influence on quality and characteristics of deposited coating.

Vencl[7] favours the plasma spray coatings and points that the plasma spray coating is widely used particular in parts of engines and compressors which the coating material is fed to a heating zone as engine and compressor cylinders. But many parameters influence the quality of coating and it is not easy to control all of them. Our proposed solutions, cylinder with tribological inserts, have a number of advantages over a longer tire life and better tribological characteristics relative to plasma spray coatings.

The main directive of tribological optimisation demands the transfer of all limit lubrication cases to hydrodynamic lubrication. In accordance with this request, it is patented the new solution of the pistons with tribological pads for use in reciprocating machines, as example for the use inside of ICEs (Fig. 6), as well as for air compressors[1].

The main task of the tribological pads, in the new piston construction, is to reduce friction between the piston and the cylinder, specifically during the engine-starting regime.

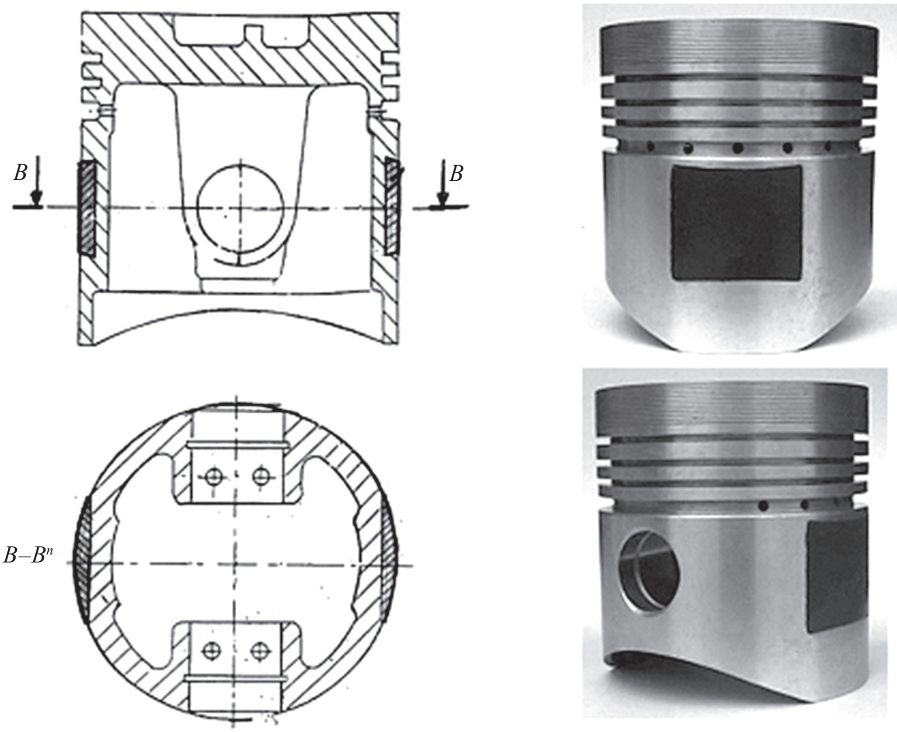


Fig. 6. Cross section of patented aluminum piston with tribological pads[1] (*a*) and image of new piston design with mounted tribological pads[1] (*b*)

Besides that, they transfer piston wear to easily replaceable pads, so in future, the repair of the piston group merely reduces to change of the worn piston rings and pads. The piston becomes only the carrier of the parts that are worn and easily replaceable.

RESULTS AND DISCUSSION

The first experiments were carried out at the Laboratory for IC engines at the FINK, on a single-cylinder, four-stroke, and air-cooled engine (model No: 3LD450, Maker: DMB – Lombardini). Main characteristics of the experimental engine are shown in Ref. 1 by Pesic.

Figure 7 shows the specific work of mechanical losses curves under operation with mounted classic grey cast iron piston as well as with new Al piston with inserted tribological pads, as the research result of the new piston construction.

The main task of the tribological pads, to reduce friction between the piston and the cylinder, is confirmed.

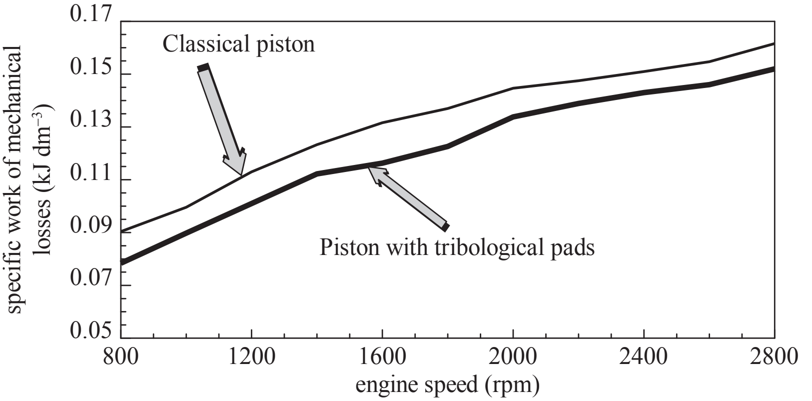


Fig. 7. Specific work of mechanical losses versus engine speed

Further researches need to be redirected on the tribological properties under dry sliding conditions, compared with grey cast iron as a standard material for cylinder block in pistons. For the optimised construction of above specified experimental reciprocating air compressor, it is important to significantly reduce lube oil consumption (LOC) towards increasing of machine performance, lowering emission and safe functionality of brake system on the vehicle inside of compressor is used. The latter is important because the presence of lube oil from air reciprocating compressor inside of exhaust (delivery) line on the vehicle can cause the local overheating and air flow restriction, resulting in undesirable malfunction of brake system.

The reduction of the LOC was therefore the prime development goal. The optimisation of the system included changes to the piston and piston rings in order to take full advantage of the APS plasma coating, too.

More details about specific machine tests during runs on the test bench[11] and/or in vehicle will be outlined inside of further researches.

CONCLUSIONS

The aim of this paper was to point the use of aluminum alloys for substitution of reciprocating machine parts made of grey cast iron. Aluminum has positive effect particularly in reduction of machine weight, but they are characterised by lesser values of stiffness and strength, and their tribological properties are relatively poor. In such cases there is a requirement to improve wear resistance of aluminum alloys, i.e. to provide at least such tribological properties like those of grey cast iron or even better ones.

With additional coating on the cylinder liner surfaces it overcomes poor aluminum strain properties. The plasma spray coating is widely used particular in parts of engines and compressors which the coating material is fed to a heating zone as engine and compressor cylinders.

Tribological inserts and pads lead to lowering friction. Our proposed solutions, cylinder with tribological inserts and piston with pads, have a number of advantages over a longer life and better tribological characteristics relative to plasma spray coatings.

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