International Congress Motor Vehicles & Motors 2014

Kragujevac, October 9th-10th, 2014

MVM2014-053

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TRIBOLOGICAL OPTIMIZATION OF RECIPROCATING MACHINES ACCORDING TO IMPROVING PERFORMANCE

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 later, the use of lightweight materials for construction of engine's accessories as it is small air reciprocating compressor for braking system of trucks and buses, has significant 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 and higher clearances during reciprocating machine operations. These high clearances would drastically increase the oil consumption and worsen the acoustic excitation. With additional coating on the cylinder liner surfaces it overcoming of poor aluminum strain properties. The application of tribological inserts towards lowering friction resulting in higher performance. The authors hope to obtain more measurement data on the test rig for small air reciprocating compressors in the Engine Laboratory at the Faculty of Engineering University of Kragujevac, which is currently being brought into operation.

KEYWORDS: Reciprocating aluminum machines, Plasma spray coating, Lowering friction

INTRODUCTION

Society relies on reciprocating machines for transportation, commerce and power generation: Internal Combustion Engines (ICEs), utility devices (e.g., compressors, pumps, portable generators, etc.). ICEs power the world's fleet of vehicles, which is passed number of one billion passenger cars and other vehicles on our roads today.

In gasoline-powered vehicles, over 62% of the fuel's energy is lost in the ICEs. IC engines are very inefficient at converting the fuel's chemical energy to mechanical work, losing energy to engine friction, pumping air into and out of the engine, and wasted heat. Advanced engine technologies such as variable valve timing, turbocharging, direct fuel injection, and cylinder deactivation can be used to reduce these losses. In addition, diesels are about 30-35% more efficient than gasoline engines [10,11].

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The popularity of Diesel engines in passenger cars is the result of their economy and improved drive ability in recent years. Diesel engines necessitate high peak cylinder pressure to ensure an appropriate torque and performance, together with low consumption and improved exhaust gas emissions. Al the more since 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 motorization 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.

At the core of these conflicting goals is the heaviest single component of the engine, the engine block and engine's accessories (water pump, alternator, fans, air reciprocating compressor …).

As example, a long list of clean technologies was reviewed for application for buses, grouped into vehicle, powertrain and fuel themes, Table 1.

Table 1 Example of low carbon technologies applicable for city buses [11]

Technologies	› Control Measures
Vehicle	• Reducing vehicle drag: Low rolling resistance tires, aerodynamic body modification • Light weighting • Predictive cruise control, platooning and driver behavior
Powertrain	• Engine: Combustion system and gas exchange system improvements, engine downsizing, lubricants for engine friction reduction, fuel additives • Parasitic losses reduction: variable flow oil and water pump, clutched compressor, smart alternator, variable speed fans • Waste heat recovery/ thermal management: Mechanical and electrical turbo compound, thermoelectric generators… • Driveline: Automated manual transmission, Continual Variable Transmission CVT • Hybridization: start stop, mild hybrid, series and parallel electric and hydraulic hybrids
Fuel	• Alternative fuels: Hydrogen (IC engines and fuel cell), electricity • Cleaner fossil fuels: Compressed natural gas … • Biofuels: Compressed biogas

Inside of powertrain system, engine efficiency is a main area for clean technologies grouped into four themes [11]:

- ✓ Combustion Systems (Injection optimization, Exhaust Gases Recirculation (EGR), Optimized Inlet Swirl, Early End of Combustion, Low Exhaust Back Pressure, Boosting, Inlet Manifold Temperature Control,
- ✓ Friction reduction (Lubricant Viscosity Specification, Piston ring design, Plasma coated cylinder liner, Piston skirt – design and coating, Crank/cylinder axis offset, Bearing design),
- ✓ Engine Accessories (Reduction in parasitic losses of engine accessories; Air reciprocating compressor – flow optimization and electric clutch, variable flow and electric oil pump, electric water pump), and
- ✓ Gas Exchange (Electric assisted turbocharger, Variable valve actuator, EGR pump).

Inside of the paper is presented the analysis regarding to the optimization of air reciprocating compressors as a contribution to reduction in parasitic losses of IC engine's accessories. Test-bench has been carried out inside of Laboratory for IC engines at University of Kragujevac, Faculty of Engineering, on a single cylinder aluminum compressor. An example how to reduce the friction by application of tribological inserts will be outlined. More details on the compressor performance and design changes made to the cast aluminum cylinder and piston, as well as cylinder head in order to take full advantage of the coating is presented in the paper from Pešić et al. [7].

STATE OF THE MATERIAL TECHNOLOGY IN PRODUCTION OF LIGHTWEIGHT METAL CYLINDER HEADS AND ENGINE BLOCKS

Modern high-performance engines place highest demands on the mechanical and physical properties of the cylinder head and the engine block. The high combustion pressure in the diesel engines require a material with extremely high tensile strength and creeping strength, thermal conductivity, ductility and elasticity combined with high thermal shock resistance and cast ability combined with low susceptibility to hot cracking.

Honing structures are being optimized on existing, proven cylinder surfaces such as cast iron blocks and sleeves, hypereutectic aluminum alloys (Alusil®), and on various galvanic coatings (e.g. Nikasil®). In parallel, the direct coating of cylinder liner surfaces with the application of thermal spray processes has become more and more important. Applying a coating directly to the cylinder surfaces in aluminum engine blocks can eliminate the need for cast iron sleeves. This can significantly reduce the weight of the engine block; leads to improved heat transfer from the combustion chamber into the cooling medium and can give corrosion protection of the liner surface.

Cylinder Heads

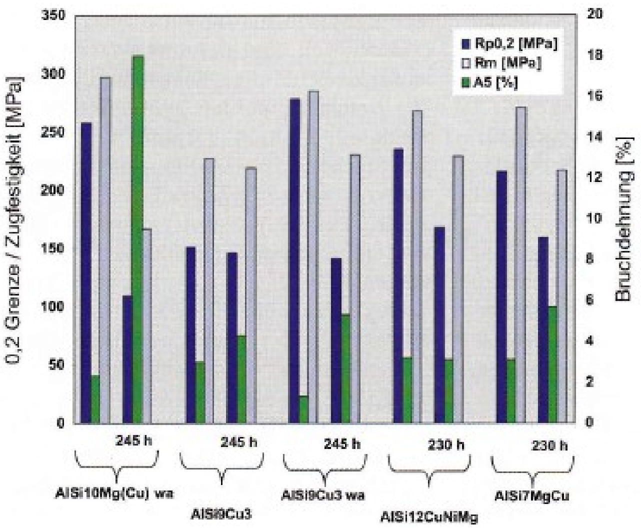
The complexity of the cylinder heads, specifically for the heavily loaded diesel engines with direct fuel injection, as well as the stress load during operation has increased significantly. The central part of the cylinder head near the combustion chamber and exhaust valve(s) are additionally subject to high temperatures ranging between 180 and 220 ^{0}C and above. In these temperature ranges can exist the mechanical problems due to fatigue strength, resulting the formation of cracks in these critical zones [2].

As an example, during the development of the alloys for the cylinder heads of the Audi V6 and V8 diesel engines, following alternative alloys examined [2]:

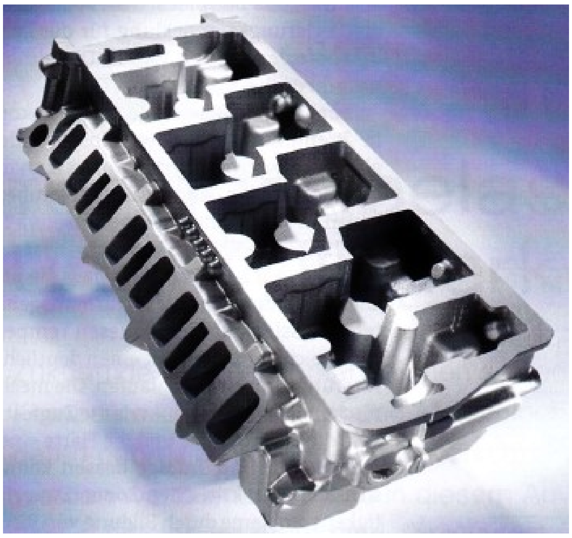
- ✓ ALSi12CuNiMg (primary alloy; the component features very good resistance to cracking, but during casting it is very susceptible to hot cracking)
- ✓ ALSi7MgCu0.5 (primary alloy; good predictability of the mechanical properties and good resistance to cracking combined with very good cast ability)
- ✓ ALSi9Cu3 (secondary alloy; very good mechanical properties combined with good cast ability).

Cylinder heads of these three alloys were examined with a view to their mechanical properties after a residence time of 230 to 240 h at 225 ^{0}C. All alloys exhibit a distinct decline in strength accompanied by increasing elongation after fracture, Figure 1 [2].

Engine tests with ALSi7MgCu0.5 provided good results for all simulated load situations [2]. Although the price for this primary alloy is slightly higher, for this application it can be considered as an ideal compromise between strength, behaviour at elevated temperatures and thermal conductivity. It guarantees, with a sufficient degree of reliability, the functioning of the cylinder head throughout its designed lifetime.



(a)



(b)

Figure 1 (a) Mechanical properties, of different casting alloys after approx. 240 h at 225 ^{0}C
(b) Cylinder head for the Audi 4.0-L V8 TDI engine in the ALSi7MgCu0.5 alloy, weight approx. 13 kg [2]

Engine Blocks

The weight of the cylinder block accounts for approx... 25 to 33% of the total engine weights depending on the size and design of the engine, the type of combustion process and the design of the crankcase. Especially, for the mass production of aluminium engine blocks most diverse concepts are used.

The strains acting on the engine block are illustrated in Figure 2. The increased specific power output leads primarily to a higher thermal strain of the cylinder liner. The direct heat induction by the combustion gas and the indirect heat induction by piston and rings particularly affect the upper part of the cylinder. As far as aluminium is concerned, its deformation due to temperature strain and the deterioration of its material properties at increased temperature (inter-bore section) have to be taken into account. In the crankcase area, where the bearing forces of the crankshaft occur, the strain rises in direct proportion to the peak pressure. Moreover, a dynamic layout of the crankcase is necessary because of the crankshaft deflection and the transmission of the combustion noise through the crank train (inner noise transfer path). The engine block must not only stand the thermo mechanical strain, but it is also supposed to form a tribological suitable bearing surface for the piston [8].

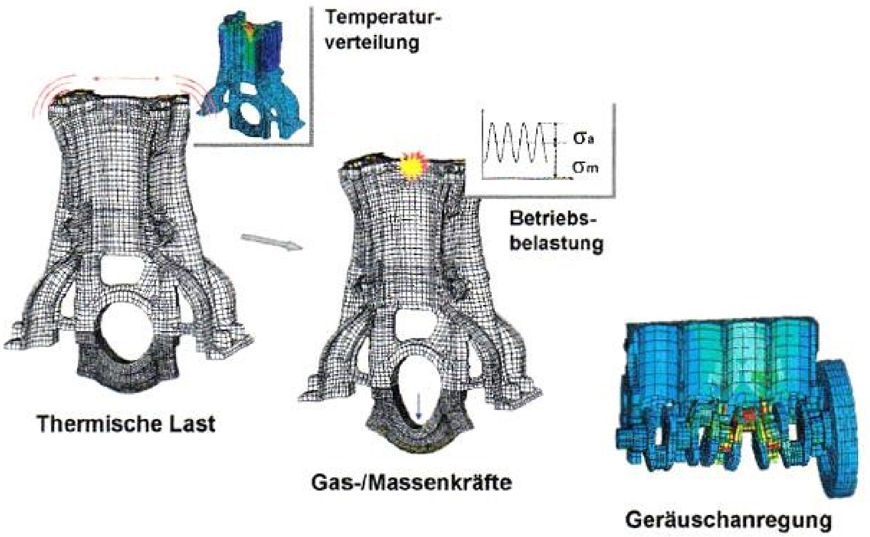


Figure 2 Loading of the engine block

As example, one material that combines almost all necessary properties is lamellar grey cast iron (GJL) or (Der lamellare Grauguss). GJL usually possesses sufficient strength and offers good tribology qualities for the cylinder liner. Its casting and processing properties are advantageous, too Figure 3. The major disadvantage of GJL material is its specific weight. The vermicular graphite cast (GJV) or (Der Vermikulargraphitguss), shares this disadvantage, but it possesses conspicuously higher degrees of stiffness and strength [8].

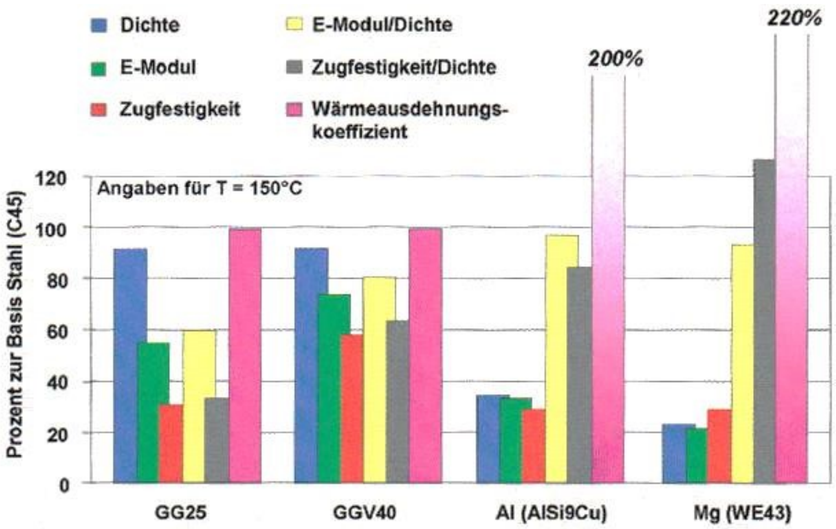


Figure 3 The properties of potential crankcase materials [8]

The advantages of aluminium and magnesium alloys show with regard to the specific weight are notable. However, they are characterized by lesser values of stiffness and strength. Both material groups have good qualities concerning the ratio of Young´s modulus and strength in comparison with mass density, which makes them suitable candidates for lightweight design. Notwithstanding this, they have considerable disadvantages in terms of thermal expansion coefficient. Without counter-measures, the greater thermal expansion would cause unacceptably high bearing clearances during engine operation. These high clearances would drastically increase the oil consumption and worsen the acoustic excitation [8].

While aluminium shows a very good thermal conductivity, the values for magnesium appear on same level as grey cast iron, so that further problems occur with regard to liner deformation and the thermal loads at the inter-bore section. Both light-weight materials necessitate additional measures for the realization of a wear resistant coating for the cylinder liner. Moreover, it has to be taken into account during the design phase that both materials have only a limited creep resistance.

In summary, it can be said that the functional demands on an engine block for high peak pressures usually can be well met by GJL materials. The GJV materials offer still higher degrees of stiffness and strength. The lightweight materials have disadvantages in this respect, but they also have the great benefit of the lower specific weight. The missing wear resistance (cylinder liner) and the high thermal expansion coefficient constitute further challenges for engines made from lightweight alloys. These drawbacks can be compensated by design measures, which cause, however, additional efforts and consequently higher costs.

The different block variants can be further broken down according to their design layout of the cover plate, cylinders and main bearing blocks. For engine blocks aluminium-silicon alloys with Si contents from 6 to 17% and copper contents from 3 to 4% are in use. Secondary alloys, such as ALSi9Cu3, account for the bulk of the casting alloys due to their favourable costs [8].

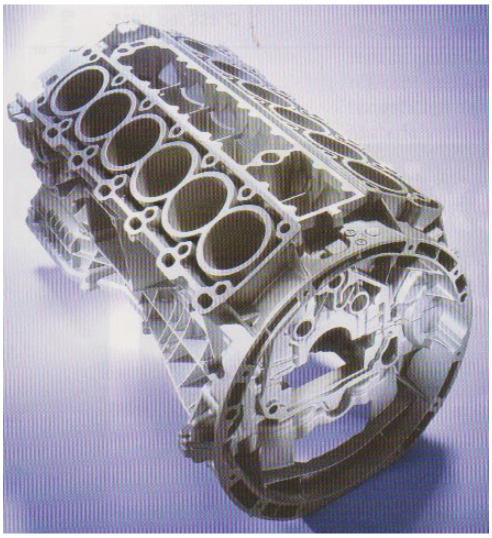
Cylinder Liner

The standard solution for the cylinder liner in the aluminium cylinder block is a liner made from cast-iron material. This liner is usually cast into the aluminium. A wall thickness of up to 1.5 or 2 mm can be achieved after machining [2].

The strain on the inter-bore section comes from the superposition of thermal stress due to the temperature profile, and the mechanic stress due to the assembly forces and the cylinder pressure. In the case of high peak pressures especially the dynamic strain increases, so that considerable deformations and stresses occur in the inter-bore section. These can be counteracted by the sufficient dimensioning and the appropriate design of the inter-bore section in combination with efficient cooling. As example for a 2.0 litre four cylinder engine intended for peak pressures of 200 bar, inter-bore section widths of less than 10 mm are difficult to realize with cast iron liners [2,8].

In case of a direct coating of the liner surface (plasma coating technique in mass production) the circumstances are a little more favourable [1,7,7,9,12]. With this method, the space gained for aluminium in the inter-bore section can be used for cooling measures, and minimum inter-bore thickness can be reduced by 1-2 mm. Plasma coatings do not only offer advantages in terms of weight, but also in terms of friction [1,8,12].

An example of a cylinder liner produced by cast-in-spray-compacted aluminium liners is the V12 cylinder engine block used in the Maybach and DaimlerChrysler´s S Class, Figure 4 (a). This engine is unique in that it features the world´s only 12 cylinder crankcase mass-produced by pressure die casting. Moreover, this design consists of the engine block and bedplate [2,10].


(a)


(b)

Figure 4 (a) 12-cylinder engine block for the Maybach and the DaimlerChrysler S-Class cast in ALSi9Cu3, block weight including the bedplate; weight approx. 38 kg
(b) 6-cylinder gasoline engine block (DaimlerChrysler) with Silitec® liners

Figure 4 (a) illustrates wear-resistant cylinder liners which consist of a hypereutectic AlSi alloy developed by PEAK Werkstoff GmbH as a lightweight alternative to the considerably heavier cast iron cylinder liners. This is also an alternative to the relatively expensive monolithic engine block made from the hypereutectic primary AlSi17Cu4Mg (Alusil®) casting alloy. The cylinder liners can then be cast-in, preferentially using the high pressure die casting process with a lower cost (secondary) AlSiCu casting alloy [1,8,12].

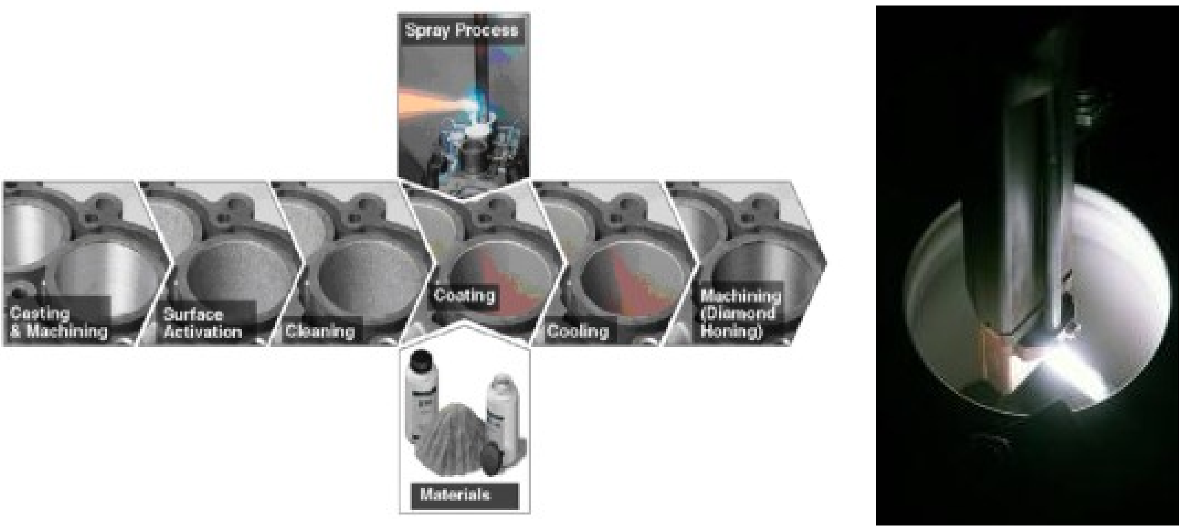
The Silitec® hypereutectic liner materials are produced by spray compaction; the spray-compacted ingots are subsequently extruded. The high solidification rate of the spray compaction process leads to significantly smaller primary silicon particles than in standard casting processes and ensures excellent tribological properties of the liner surface after the special honing process, Figure 4 (b). Since the same base material is used, metallic bonding between the liner and the engine block is achieved over more than 50% of the contact surface. The result is an engine block showing low distortion and high dimensional stability [1,12].

APPLICATION OF TRIBOLOGICAL METHODS DURING CONSTRUCTION AND PROCESSING OF RECIPROCATING MACHINES

The main parameters which the designers need to know are friction, wear and service life of the machine's 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 later, need to be improved wear resistance of the aluminium alloys to provide their tribology similar to grey cast iron [1].

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. Consequently, it exists more of methods have been examined or actually applied for the surface coating of aluminum cylinder liners.

Applying a coating directly to the cylinder surfaces in aluminium 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 aluminium 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 Figure 5 (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, Figure 5 (b) [1,12].

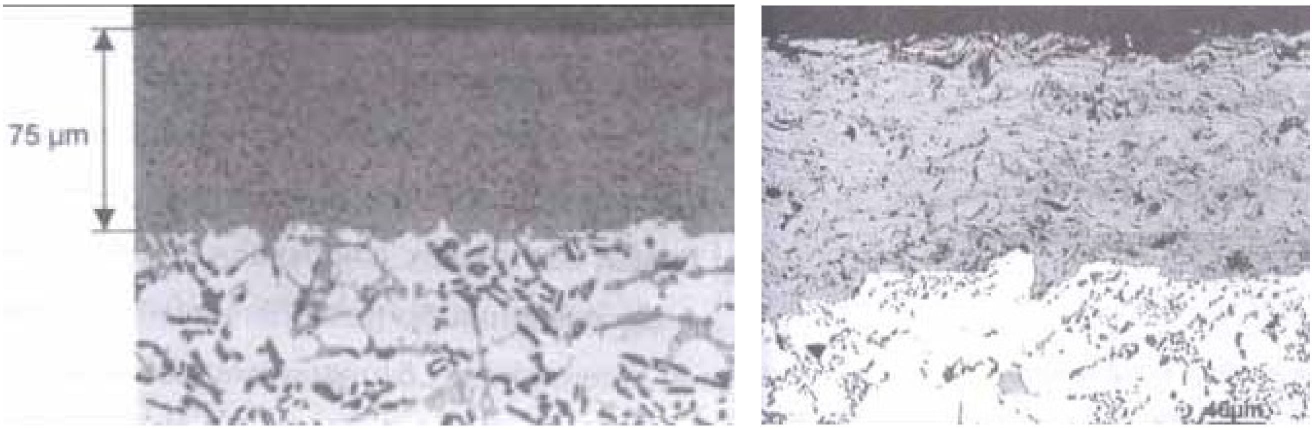


(a) (b)

Figure 5 (a) Schematic representation of the SUMEBore coating process (from left to right, including honing) (b) F210 plasma torch in an ø81 mm bore of an aluminum engine/ gas compressor block [1,12]

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 hot plasma plume, where it is melted and propelled towards the target substrate to form the coating [1,12].

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, Figure 6 [9,12]



(a) (b)

Figure 6 (a) Micrograph showing Ni-SiC dispersion layer (Kolbenschmidt)
(b) Micrograph showing plasma coating layer (Sulzer Metco)

Piston Rings Coating – An example of tribological optimization

Other applicable methods include laser coating of an AlSi alloy, physical (PVD) and chemical vapor deposition (CVD), etc., using materials such as diamond-like carbon (DLC), chromium nitride, titanium nitride, i.e. many different surface coating structures and chemistries [1,4,12].

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, Figure 7. At the same time measures such as direct injection and turbocharging among others, which increase engine performance, intensify the requirements for the functional behavior of piston rings [4,11].

When considering measures to optimize 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 behavior 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 behavior and offers a considerable potential to reduce frictional losses.

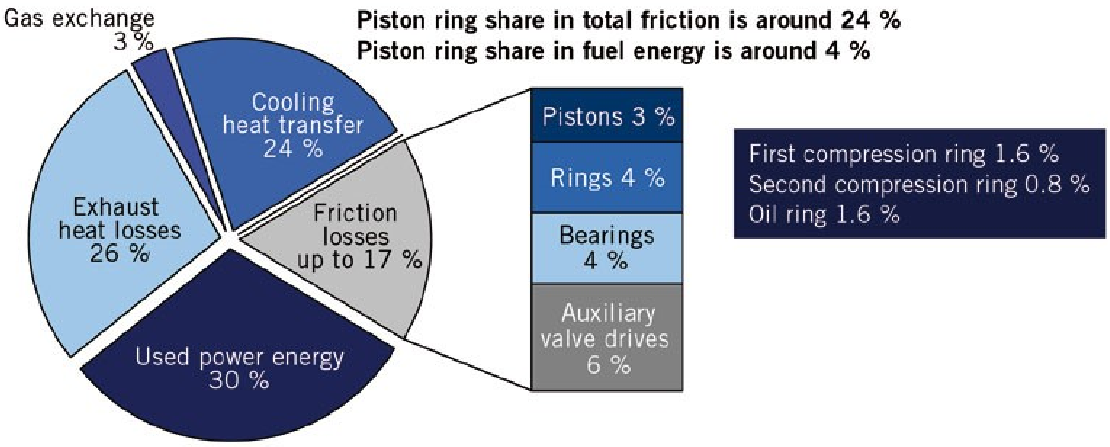


Figure 6 Energy distribution diagram showing friction losses in gasoline engines with the proportionate share of the piston rings [4]

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 [1,12].

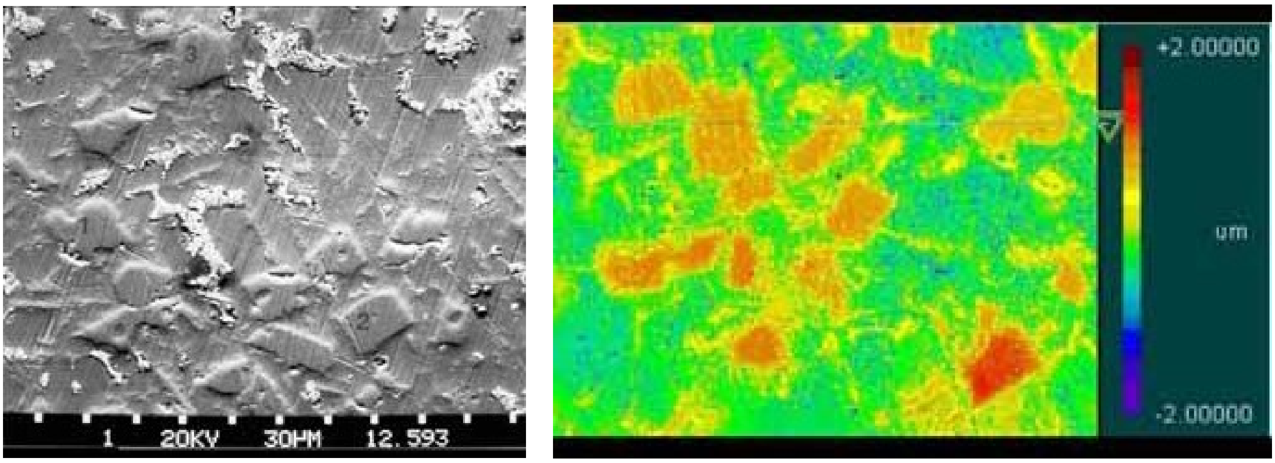
The new coating combines extremely low friction values with high strength and durability of piston rings and cylinder running surfaces. By using this coating, the ring pack's frictional losses can be reduced by up to 20%. It significantly protects the cylinder running surface against scoring, increased 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 [4].

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 [1,9,12]:

- ✓ 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 aluminum matrix and an exposure of the silicon 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 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. 7.



(a) (b)

Figure 7 (a) Micrograph showing the final surface after honing with recessed AL matrix and exposed Si particles
(b) Image from white light interference microscope showing the topography of the final cylinder surface

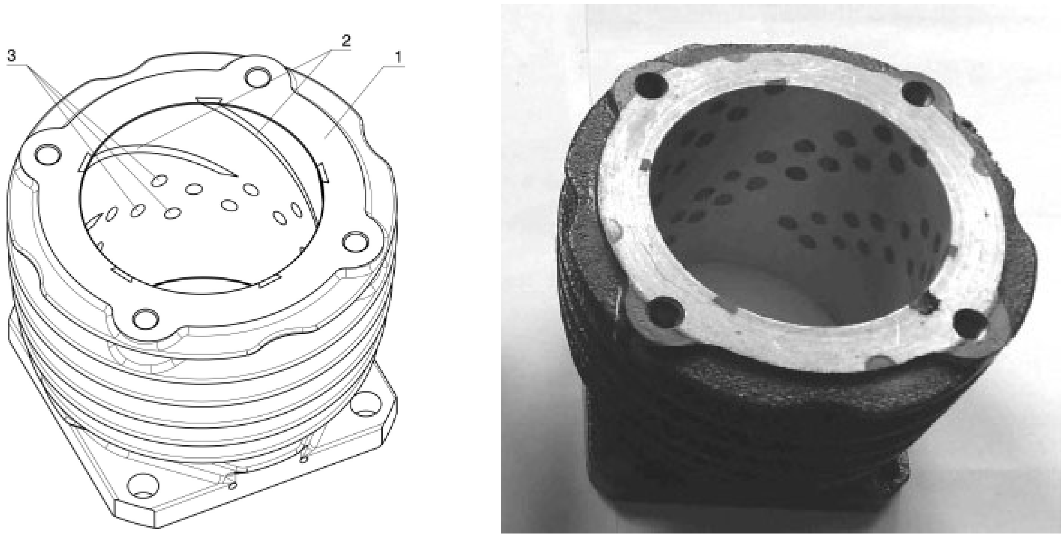
The new concepts piston and cylinder

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 aluminium alloys [3,7]. The previous was traditionally made from grey cast iron. The compressor is currently being experimentally investigated on a custom test rig for small air compressors in the Engine Laboratory of the Faculty of Engineering, University of Kragujevac (FINKG) [5,6,7].

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. But if we looking generally, most aluminium alloys, specifically those suitable for mass production from the technological and economic aspect, do not have satisfactory wear resistance, i.e. their tribological properties are relatively poor. In such cases there is a requirement to improve wear resistance of aluminium alloys, i.e. to provide a least such tribological properties like those of grey cast iron or even better ones. According to this, the surface engineering of the engine cylinder liner is in the focus of most producers of aluminium reciprocating machines [1,7,10,11,12].

According to the latter, as a contribution, patented is the AL cylinder for experimental reciprocating air compressor, coated inside by air plasma spray process (APS). Applied coating materials have good resistance to wear (appropriate steel or cast iron) and good mechanical and tribological properties, Figure 8 [3,7], where the continual tribological pads (2) and/or discrete tribological pads (3) are set into a cylinder (1) in the part over which piston rings slide during operation. These methods are applicable to improve tribological 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 are the one that define possible application of material, far more than their mechanical properties, since they are in better correlation with behaviour in practice.

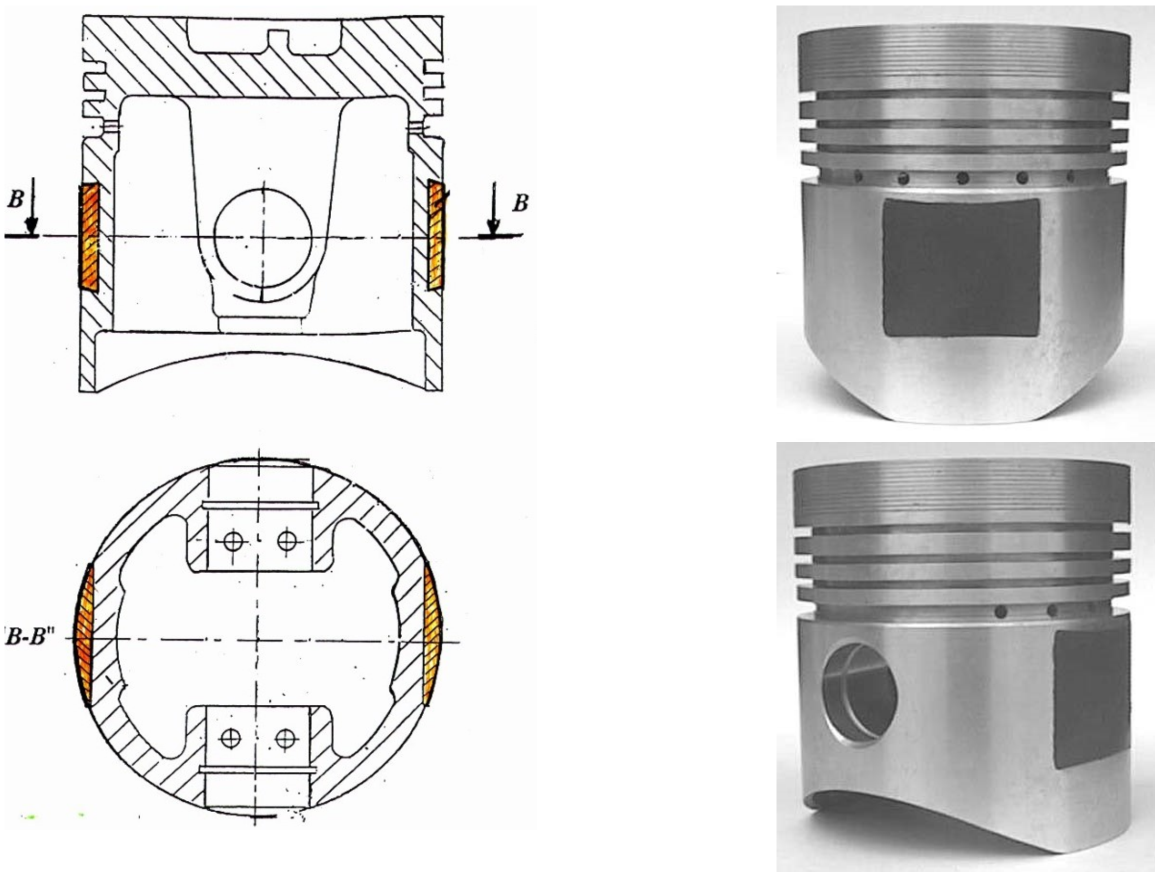
However, more measurement data are required before a fully qualified statement as to its general utility can be made. There are a great number of parameters that influence on quality and characteristics of deposited coating.



(a) (b)

Figure 8 (a) Cross section of patented aluminum cylinder with tribological pads (2-continual and 3-discrete pads)
(b) Single aluminum cylinder that was used as a technology demonstrator at FINKG [2,7]

The main directive of tribological optimization 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, Figure 9, as well as for air compressors [7].



(a) (b)

Figure 9 (a) Cross section of patented aluminum piston with tribological pads
(b) Image of new piston design with mounted tribological pads [7]

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.

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.

EXPERIMENTAL INVESTIGATIONS

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 the paper from Pesic et al. [7].

Figure 10 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 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.

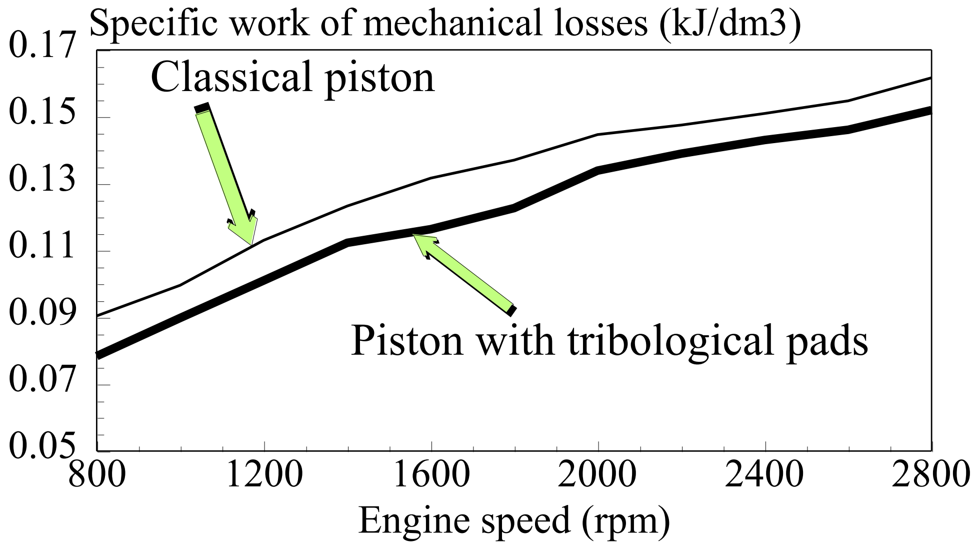


Figure 10 Specific work of mechanical losses vs. engine speed

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 an pistons. For the optimized 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 optimization 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 and/or in vehicle will be outlined inside of further researches.

CONCLUSION

(1) The use of aluminium alloys for substitution of reciprocating machine parts made of grey cast iron has positive effects in term such as reduction of machine weight, but they are characterized by lesser values of stiffness and strength, and their tribological properties are relatively poor.

(2) The greater thermal expansion of aluminium construction would cause unacceptably high clearances during machine operation. These high clearances would drastically increase the oil consumption and worsen the acoustic excitation. In such cases there is a requirement to improve wear resistance of aluminium alloys, i.e. to provide a least such tribological properties like those of grey cast iron or even better ones.

(3) 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. Consequently, it exists more of methods have been examined or actually applied for the surface coating of aluminum cylinder liners. Inside of our researches is interesting the atmospheric plasma spray process.

(4) With additional coating on the cylinder liner surfaces it overcoming of poor aluminum strain properties. The application of the piston with tribological inserts towards lowering friction resulting in higher performance of reciprocating machine.

ACKNOWLEDGMENTS

The paper is a result of the research within the project TR 35041 financed by the Ministry of Science and Technological Development of the Republic of Serbia.

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International Congress
Motor Vehicles & Motors 2014

VEHICLE AS A SAFETY FACTOR OF THE TRANSPORTATION ACTIVITY

Proceedings

October 9th - 10th, 2014
Kragujevac, Serbia

Publisher:	Faculty of Engineering, University of Kragujevac Serbia, 34000 Kragujevac, Sestre Janjić 6
For Publisher:	Prof. dr Miroslav Živković - Dean
Editors:	Dr Božidar Krstić, prof. Dr Dragan Taranović, assist. prof.
Technical preparation:	Dr Dragan Taranović, assist. prof.
Picture on the cover:	Nemanja Lazarević
Print CD:	Faculty of Engineering, University of Kragujevac, Kragujevac
	ISBN 978-86-6335-010-6
Year of publication:	2014.
Number of copies printed:	200

CIP - Каталогизација у публикацији
Народна библиотека Србије, Београд

629.3(082)
621.43(082)

INTERNATIONAL Congress Motor Vehicles & Motors (5th ; 2014 ; Kragujevac)
Vehicle as a Safety Factor of the Transportation Activity : proceedings / International Congress Motor Vehicles & Motors 2014, [5], October 9th-10th, 2014, Kragujevac, Serbia ; [congress organizers Faculty of Engineering, University Kragujevac ... [et al.] ; editors Božidar Krstić, Dragan Taranović]. - Kragujevac : Faculty of Engineering, 2014 (Kragujevac : Faculty of Engineering). - IX, 546 str. ; 30 cm

Tiraž 200. - Napomene i bibliografske reference uz tekst. - Bibliografija uz svaki rad.

ISBN 978-86-6335-010-6

Publishing of this book is supported by:

Ministry of Education, Science and Technological Development of the Republic of Serbia