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Saša Milojević[1]
Dragan Džunić[2]
Dragan Taranović[3]
Radivoje Pešić[4]
Slobodan Mitrović[5]

EXPERIMENTAL DETERMINATION OF TRIBOLOGICAL CHARACTERISTICS OF COMPOSITE MATERIALS IN USE FOR PARTS IN ALUMINUM AIR COMPRESSOR (PISTON AND CYLINDER)

ABSTRACT: For reciprocating machines are applicable different materials for the piston skirt and piston rings as well as for cylinder liner. The friction and wear of the piston group is highly dependent by the material and the honing of cylinder liner, the coating characteristics, the piston ring dimensioning and tension. If using aluminum alloys for producing of piston and cylinders in engines and compressors, the results are lower fuel consumption and exhaust emission, firstly because of lower weight and mechanical losses, too. The problems are poor tribological characteristics and lower strength of unprotected aluminum comparing with gray cast iron. In this paper, the tribological properties of ferrous and graphite based reinforcements were analyzed and compared with aluminum alloy as a base material for cylinder liner and piston skirt in air brake compressor. The ball–on–plate CSM nanotribometer was used to carry out these tests under dry sliding conditions and constant sliding distance, for three different values of sliding speed and normal loads.

KEYWORDS: air compressor, aluminum MMC, reinforcements, tribology

INTRODUCTION

Heavy–duty vehicles, trucks and buses are responsible for about a quarter of carbon dioxide (CO_2) emissions from road transport in the EU and for some 6% of total EU emissions. Transport is the only major sector in the EU where greenhouse gas emissions are still rising. The European Commission has therefore set out a strategy to curb (CO_2) emissions from these vehicles over the coming years. Emissions from transport could be reduced to more than 60% below 1990 levels by 2050 [1].

[1] *Mr Saša Milojević, assistant R&D. University of Kragujevac, Faculty of Engineering, Kragujevac, Sestre Janjić 6,* sasa.milojevic@kg.ac.rs
[2] *Dr Dragan Džunić, assistant prof. University of Kragujevac, Faculty of Engineering, Kragujevac, Sestre Janjić 6,* dzuna@kg.ac.rs
[3] *Dr Dragan Taranović, associate prof. University of Kragujevac, Faculty of Engineering, Kragujevac, Sestre Janjić 6,* tara@kg.ac.rs
[4] *Dr Radivoje Pešić, prof. University of Kragujevac, Faculty of Engineering, Kragujevac, Sestre Janjić 6,* pesicr@kg.ac.rs
[5] *Dr Slobodan Mitrović, prof. University of Kragujevac, Faculty of Engineering, Kragujevac, Sestre Janjić 6,* boban@kg.ac.rs

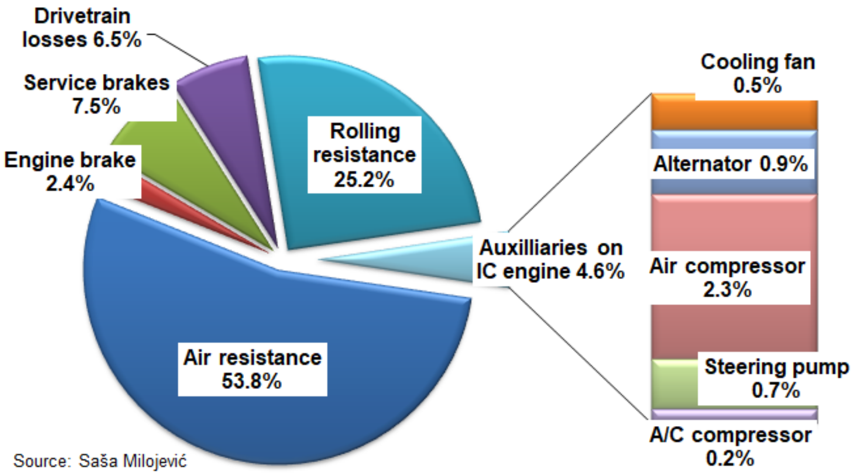


Figure 1 Share of driving resistances and auxiliary power demand on the total fuel consumption of a semi–trailer truck Euro V

In city buses and trucks a lot of fuel energy is engaging for power of auxiliary units. Specifically, the fuel energy is engaged for drive of periphery units on engine, as example, for the air compressor, the alternator, the steering pump, the oil pump, the coolant pump, the fuel high pressure pump and the fuel delivery pump, as well as for air conditioning (A/C) compressor. The share of auxiliaries on the total power consumption is especially high for city buses (6.5%) due to (A/C) system and additional consumers of electricity and pressurized air, Figure 1 [1, 2].

Reasons for this are the higher air demand of the wheel brakes, fewer headwinds for the engine cooling or more steering in curves *i.e.* the main influence factors on fuel consumption are the engine off heat or the wheel brakes air demand. As a result, an increasing losses resulting in increase of fuel consumption, that is directly proportional to emission of (CO_2). Generally, city buses are associated with 4.4% of total (CO_2) emissions [1]. City buses are frequently purchased by public institutions and thus they are in the public eye, yet may be the focus of cost–cutting measures [2–8].

In order to reduce exhaust emission, the vehicles equipped with a conventional internal combustion engines must be optimized by lowering the mechanical losses, specifically internal friction of the mechanical parts in sliding contacts. Potential actions to reduce friction in vehicles 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 [9–11].

In accordance with the above mentioned facts, we have realized the research in the field of optimal design of reciprocating aluminum engines and compressors. Consequently, we investigated new option for increasing strength and tribological properties of the tribo-system piston–cylinder liner [12–15].
The result of researches is patented prototype of aluminum piston and cylinder whose contact surfaces are coated or modified with reinforcements based on the tribo–materials [16, 17].

METHODS FOR MACHINING OF CYLINDER SURFACE WHICH IS IN SLIDING CONTACT

As the mechanical efficiency of the aluminum internal combustion (IC) engines *i.e.* reciprocating machines is strongly influenced by the tribological situation between piston, piston ring and cylinder surface, the properties of the cylinder surface become particular significant. Specifically, because the tribological properties of pure aluminum are poor compare with grey cast iron.

Generally, aluminum alloys have specific disadvantages in the form of higher coefficient of thermal expansion and inadequate tribological (friction and wear) and mechanical (lower strength) properties.

From the second side, aluminum composites show high stiffness, strength and wear resistance. The elastic modulus could reach values up to 220 GPa. Conventional aluminum alloys have the elastic modulus of (70–80 GPa). The elastic modulus could be changed by alloying elements, ceramic particles and fibers [18–20].

High-silicon-alloys are made mostly via spray forming. For technical application silicon contents up to 36% are in use for pistons, cylinder liners and other high temperature components. These technical aluminum–silicon–alloys show the elastic modulus of (85–100 GPa) and good wear resistance. The machining behavior is good compared to conventional cast aluminum–silicon–alloys [18].

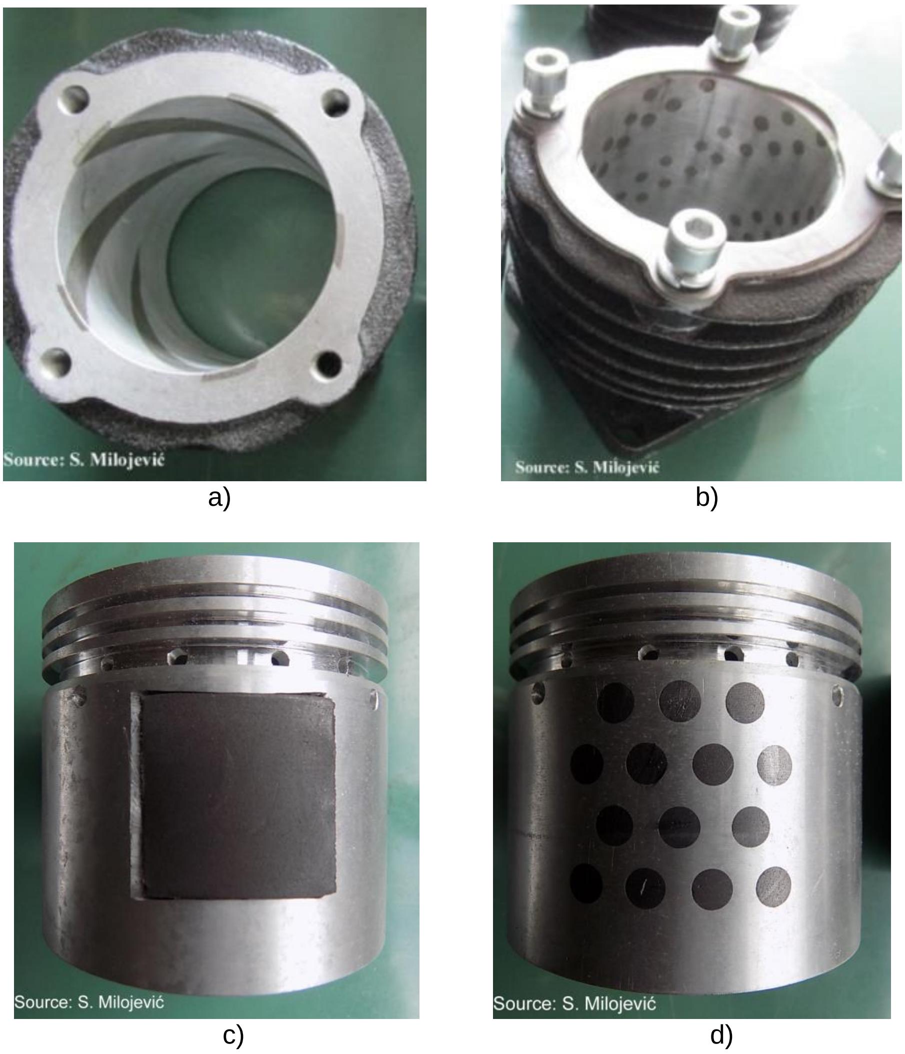


Figure 2 Photography of aluminum cylinder and pistons with tribological reinforcements
a) Cylinder with continual plates; b) Cylinder with discrete plugs in the form of spheres or nodule;
c) The piston with the interchangeable tribological inserts (in area of the piston skirt) and
d) The piston skirt reinforced with discrete plugs in the form of spheres or nodule

Thermal spray coatings are one of option to provide protection of aluminum alloy. Thermal spraying techniques are coating processes in which melted (or heated) materials are sprayed onto a surface. Today, any makers utilize thermal spraying as one of most predominant surface treatments, to making fully sprayed cylinder surface consisting of (Fe–Al) composite material [20].

Looking from the second side, liquid–type lubricants have effectively served in reducing the friction and wear of various mechanical devices. However, in compressor components, the liquid-type lubricants have negative effects on their thermodynamic efficiencies, and also the state of lubrication in these components is usually not known and is considered to be in the boundary and mixed lubrication regimes. Recently, research interest and efforts are on oil–less compressor conditions to eliminate the adverse effects of liquid–type lubricants and to further improve the performance of compressors. Consequently, it becomes necessary to develop advanced coating materials that exhibit lower friction and higher wear resistant under compressor specific conditions [21–25].

New concept of aluminum cylinder with tribological reinforcements

Generally, according to real machining conditions, the full contact between piston rings and cylinder is not possible. This fact leads us to the idea that by casting tribological inserts in the cylinder, we can determine in forward, contact area between piston rings and cylinder liner.

With the aim to achieving strength as well as tribological characteristics similarly as in case of the application grey cast iron, we patented the cylinder of composite material for reciprocating air compressor with the reinforcements consisting of tribological materials, Figure 2 [20].

For the purposes of the experiment, internal surface of the aluminum cylinder as base material–matrix, (alloy EN AlSi10Mg), was modified by putting tribological reinforcements of cast iron that are arranged in the form of continuous pads, the plates or like discrete tribological plugs in the form of spheres (nodule), or particles spherical shape, as reinforcements [20].

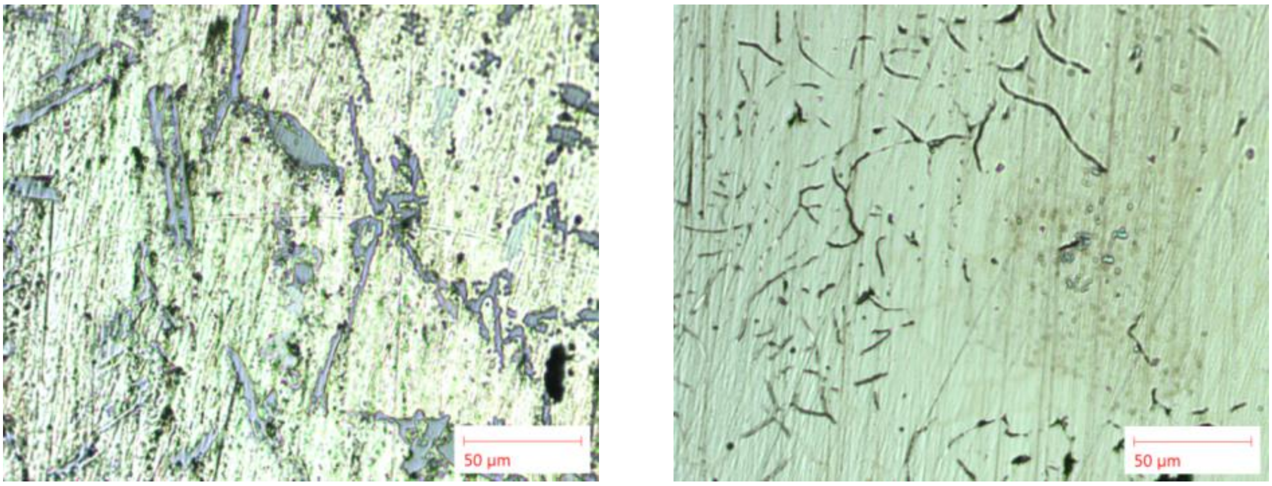
By transferring the contact between the piston rings and cylinder made of aluminum on the tribological inserts, we reduce the wear. This technology extends the service life of cylinder and piston rings.

This optimization can lead to reduce machine weight as well as reduced friction and wear. A reduction of friction between piston rings and the cylinder running surface is particularly effective, because the majority of frictional losses in the reciprocating machines are generated inside of this tribological system [9, 24].

EXPERIMENTAL RESEARCHES

Wear is progressive loss of material caused by friction resistance between contact surfaces. The present work wants to investigate and evaluate the effect of tribological plugs as reinforcements on tribological behavior of patented aluminum cylinder.

Tribological tests were carried out at CSM nanotribometer with ball–on–plate contact pair for different normal loads and sliding speeds in dry conditions. Tribological tests are based on variation of three different normal loads (0.3, 0.6 and 0.9) N and sliding speeds (3, 9 and 15) mm·s^{-1}. Duration of each test was 500 cycles (distance of 1 m), acquisition rate 100 Hz [26, 27].



a) b)

Figure 3 Optical microscopy for: a) Base aluminum alloy; b) Cast iron reinforcement

Continuous wear monitoring during linear reciprocating sliding was investigated. Coefficient of friction (COF) and penetration depth (PD) curves were obtained and analyzed. We continually monitor wear process by PD parameter and we examine effects of changes in applied load and speed.

RESULTS OF TRIBOLOGICAL TESTS AND DISCUSSION

Optical microscopy analysis

Experiments were carried out with the base material for cylinders (aluminum alloy) and with the material for reinforcements made of cast iron. Figure 3.a presents optical microscopy of base aluminum alloy surface, where grey phases, which are noted on the surface, presents eutectic silicon. Figure 3.b presents surface of cast iron nodular discrete pads (reinforcements). Deeper analysis of the presented surface revealed that black lines across the surface are not micro cracks but graphite inclusions in the cast iron.

More detail analysis of prepared samples, both of aluminum alloy and cast iron inclusions were performed using Phenom ProX Energy–Dispersive Spectroscopy (EDS). EDS analysis results are presented on the Figure 4 and 5.

Figure 4 presents EDS analysis of aluminum alloy and it noticeable that are present three phases, white one iron particles trapped in aluminum alloy as a result of grinding process. Lighter grey zones represent eutectic silicone, which is constituent element of the aluminum alloy, while dark grey represent pure aluminum.

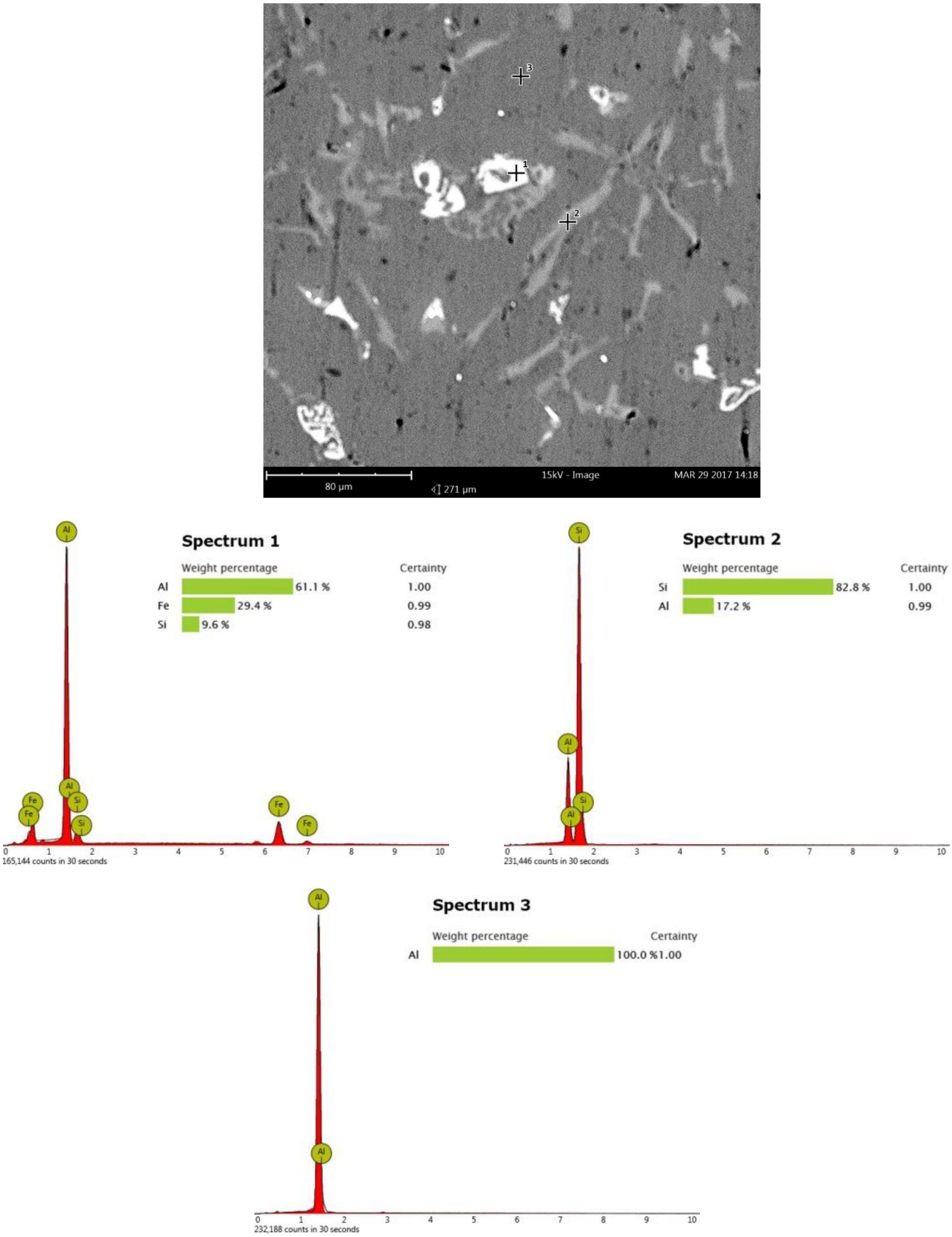


Figure 4 EDS analysis of base aluminum alloy

Figure 5 represents EDS analysis of cast iron inserts, and it is noticeable that only two phases exist. Black phase represent graphite inclusions as is it is previously assumed based on optical microscopy. White phase represents pure iron, although graphite is present, which can be seen on spectrum 2.

Higher percentage of graphite in this phase is, also, result of grinding and polishing process that smears graphite inclusions all over the surface.

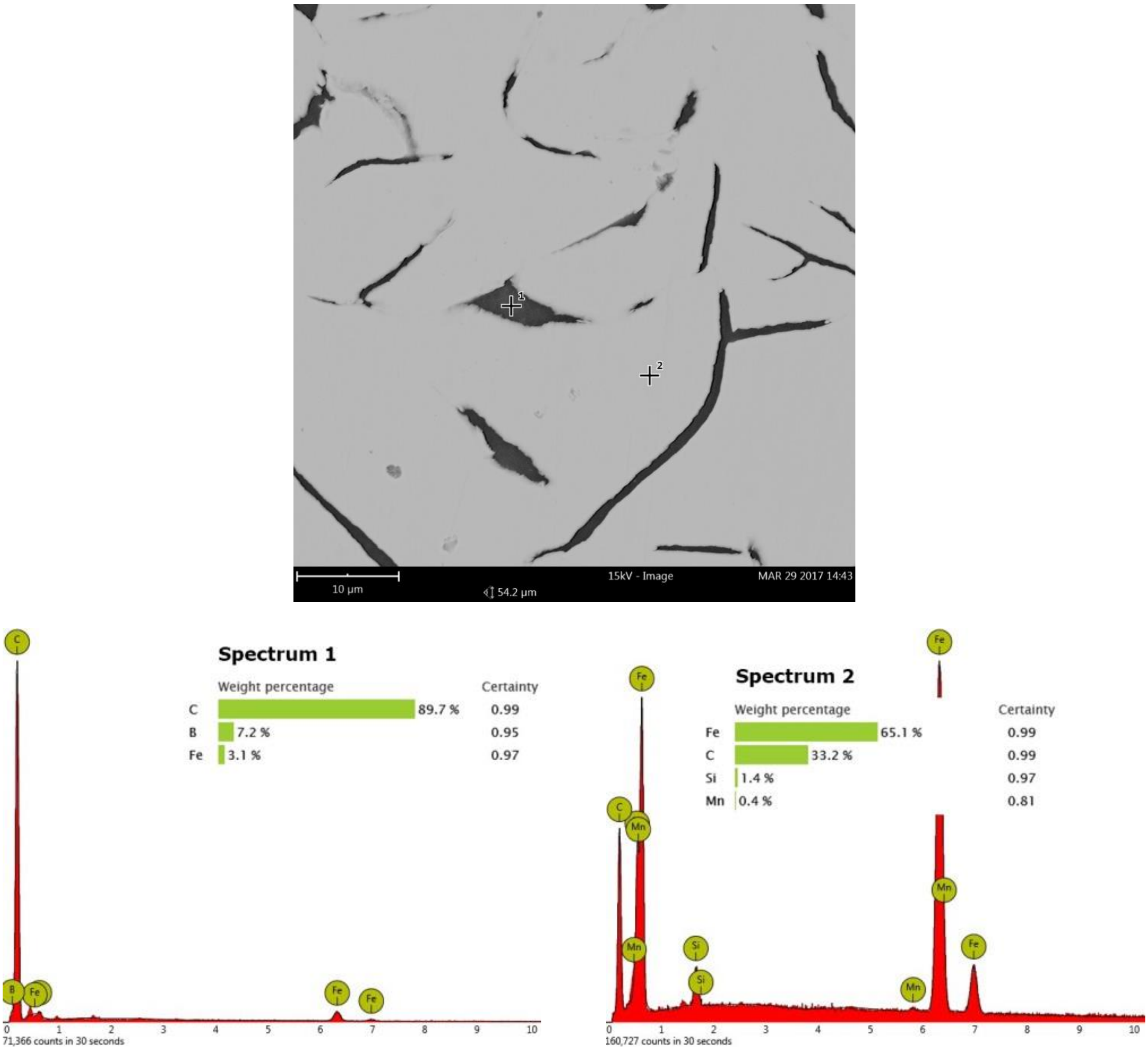


Figure 5 EDS analysis of cast iron inserts

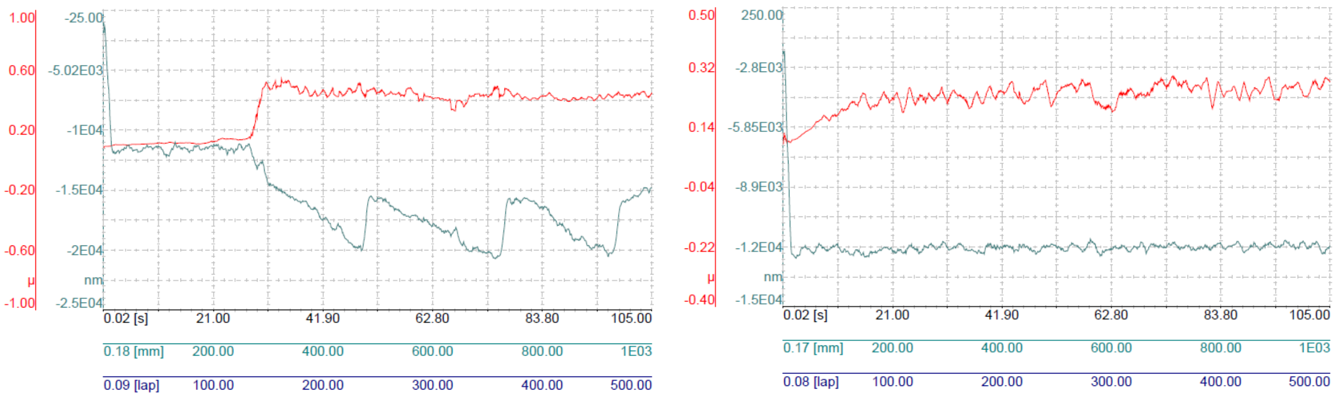
Coefficient of friction and penetration depth

Changes of COF and PD (ordinate) during sliding under low load conditions, depending on time, distance and numbers of cycles (abscissa) are shown in Figure 6.a for basic material (aluminum) and in Figure 6.b for tribological reinforcement. Due to the reciprocating motion of the needle of CSM nanotribometer between two end positions, the friction force was also changing direction during the test.

The values of COF for tribological reinforcement were ranging from (0.09–0.295), and these maximal values are lower to the results of base material (0.083–0.543). The mean value of COF for the reinforcements is also lower (0.232) relative to the value for the base material (0.350). A steady–state value for COF was reached shortly after the beginning of the test. PD in material of reinforcements has stable and constant values compared to base material.

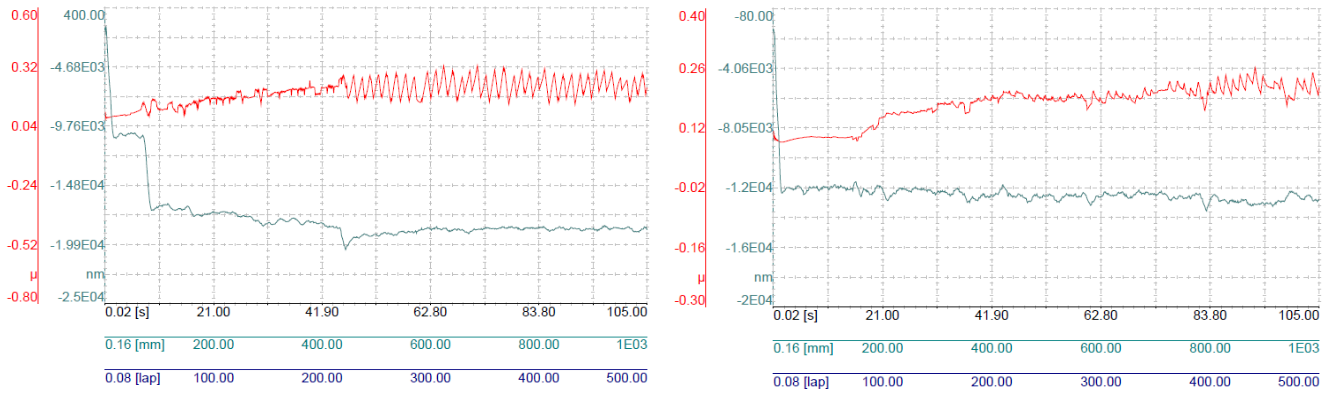
Under higher load conditions and same sliding speed, a lower maximum value of COF of the reinforcement was also recorded, too, Figure 7.a and Figure 7.b. The obtained COF values range in the range (0.087–0.262) for the reinforcements, and (0.076–0.327) for the base material. The mean value of COF of the reinforcements is lower (0.176) than the value for base material (0.202).

It is noticeable that during wear testing of base material (aluminum alloy) COF sharply rises after a certain period of sliding as result of material transfer on counter body steel ball. After the material was transferred on the steel ball contact between transferred aluminum and aluminum as a base material was achieved, which result in increase of COF value. This process happens regardless the applied load, and it has cyclic nature, which indicates that transferred material on the counter body surface accumulates until it reaches critical size, that cannot bear tangential loads. Penetration depth plot (Figure 6.a and Figure 7.a) confirms this assumption. After reaching critical size, transferred material will fall off and process of transferring starts from the beginning.



a) b)

Figure 6 Filtered signal of coefficient of friction and penetration depth for:
a) Base material under ($F_N = 0{,}3\ N;\ V = 15\ mm \cdot s^{-1}$); b) Reinforcements under ($F_N = 0{,}3\ N;\ V = 15\ mm \cdot s^{-1}$)

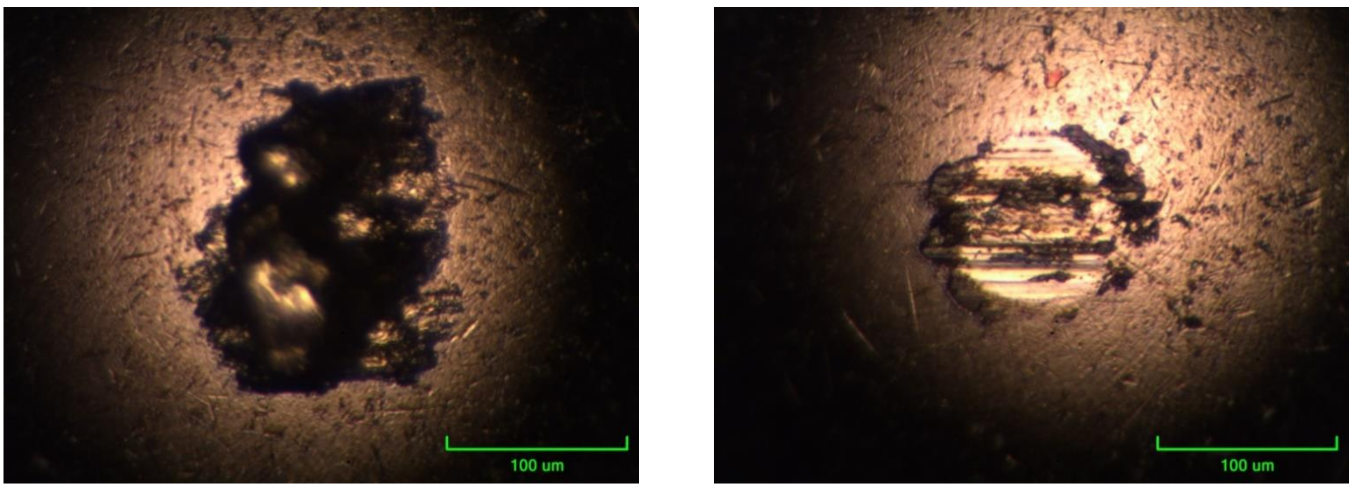


a) b)

Figure 7 Filtered signal of coefficient of friction and penetration depth for:
a) Base material under ($F_N = 0{,}9\ N;\ V = 15\ mm \cdot s^{-1}$); b) Reinforcements under ($F_N = 0{,}9\ N;\ V = 15\ mm \cdot s^{-1}$)

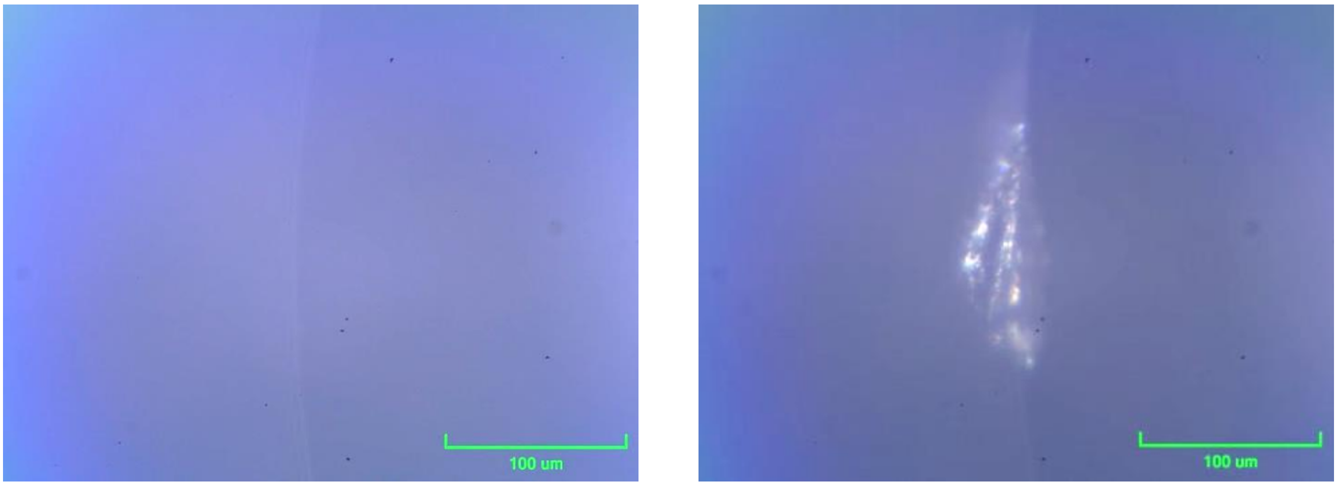
In case of wear testing of cast iron inserts (reinforcements) no transfer material was observed, which is also confirmed by COF and penetration depth curves regarding applied load value. Both measured values, COF and penetration depth has almost constant averaged value during wear testing.

In addition to this conclusion, Figure 8 clearly indicates accumulated transferred material on the counter body steel ball surface after sliding tests of base material (aluminum alloy) and no transferred material on counter bod surface after sliding test of reinforcement (cast iron). To be sure that transfer of material took place, counter body steel ball profile was examined, Figure 9.



a) b)

Figure 8 Optical microscopy of the counter body steel ball profile after sliding test:
a) Base material (aluminum alloy); b) Reinforcement (cast iron inserts)



a) b)

Figure 9 Optical microscopy of the counter body steel ball profile a) before and b) after sliding test

Figure 9.b clearly indicates accumulated transferred material on the counter body surface.

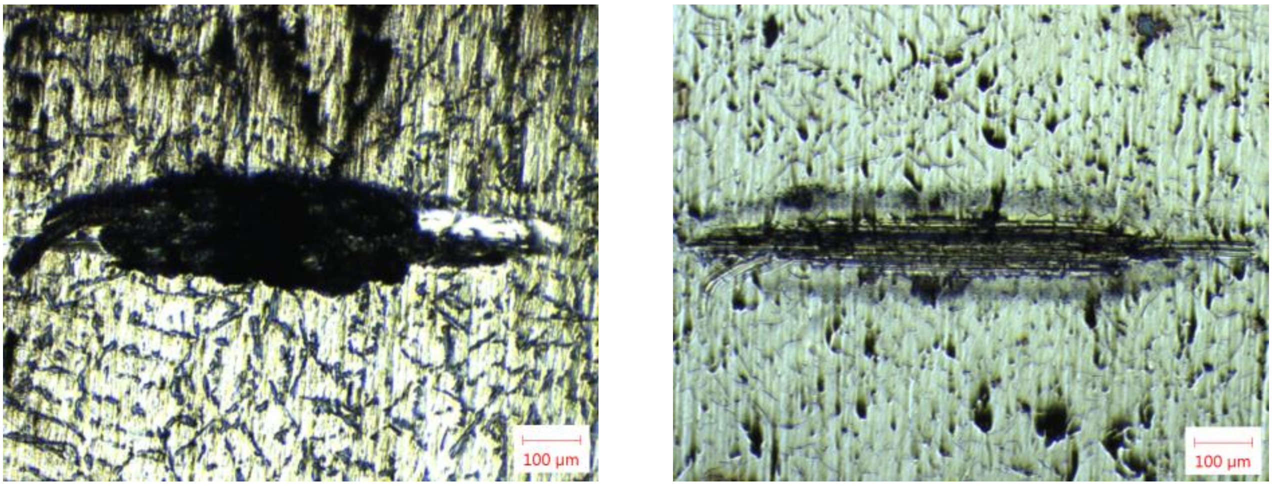
Wear analysis

Wear mechanisms based on examinations of worn surfaces by optical microscopy, were analyzed in comparison with trends of PD curves. Figure 10.a and 10.b present surface micrographs of base material and reinforcements after test under dry sliding, obtained for the same conditions of applied load and speed. It is noticeable that wear of aluminum is higher than cast iron sample due to transfer material and increase of COF which occurs for aluminum.

Prior wear tests, mechanical characterization of the prepared samples have been performed. Hardness tests were performed using CSM NHT2 nanoindenter, using Berkowich three sided diamond tip. Nine measurements for each tested material were done and averaged hardness values for base material and for reinforcement are 90 and 318 Vickers, respectively. Divergence in hardness values of tested materials indicates in better wear resistance of reinforcement in comparison to the base material.

Deep grooves in analyzed surfaces, indicates that the abrasive wear is the most dominant mechanism of wear for both tested materials, although transfer material on the counter body should not be neglected, especially for aluminum alloy.

Similar conclusions can also be made when testing materials at lower load and at the same sliding speed ($\mathrm{F_N} = 0{,}3\ \mathrm{N};\ \mathrm{V} = 15\ \mathrm{mm \cdot s^{-1}}$) [26].



a) b)

Figure 10 Surface micrographs after dry sliding test for:
a) Base material under ($F_N = 0.9\ \mathrm{N};\ V = 15\ \mathrm{mm \cdot s^{-1}}$); b) Reinforcement under ($\mathrm{F_N} = 0.9\ \mathrm{N};\ \mathrm{V} = 15\ \mathrm{mm \cdot s^{-1}}$)

CONCLUSIONS

- In trucks and city buses a lot of fuel energy is engaging for power of auxiliary units of engine, as it is air compressor inside braking system, reciprocating compressor for air conditioning system, pump of the steering system, alternator etc.;
- The use of aluminum alloys for making parts of propulsion and mobile systems is important from the aspect of weight reduction, which directly affects the reduction of fuel consumption. On the other hand, the problems in application are lower strength and poor tribological characteristics of aluminum as well as aluminum constructions;
- Some of the available ways to improve the tribological and mechanical properties of the aluminum made parts are application of coatings with tribological materials, the texture surface making technology, the application of lower viscosity oils and additives in lubrication oil;
- The problems of lower strength as well as the poor tribological characteristics of the cylinder for application in reciprocating air compressor for brake system of bus have solved by application aluminum matrix composite material. One of the constituents is aluminum alloy (EN AlSi10Mg) as the base material or matrix. Second constituent is being inserted into base material and serves as reinforcement which is made of cast iron in the form of particles of a spherical shape;
- Presented results of the researches, obtained during tests of materials from which consisting cylinder, shows that by transferring the contact between the piston rings and cylinder made of aluminum on the reinforcements, it is possible to reduce the friction and wear. This technology extends the service life of cylinder and piston rings; and
- Based on the results of tribological tests, more favorable characteristics of the friction and wear of the reinforcements in relation to the base material were confirmed. The obtained results are useful as guidelines for further research and selection of the appropriate cylinder construction within the optimization of the performance of the experimental piston compressor for the production of compressed air on the heavy–duty vehicles (on buses and trucks).

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