FERROUS-BASED COATINGS FOR ENGINE CYLINDER BORES MADE OF ALUMINIUM ALLOYS: TRIBOLOGICAL PROPERTIES

PREVLAKE NA BAZI GVOŽĐA ZA BLOKOVE MOTORA IZRAĐENE OD LEGURA ALUMINIJUMA: TRIBOLOŠKE KARAKTERISTIKE

Aleksandar Vencl
Tribology Laboratory, Mechanical Engineering Faculty, University of Belgrade, 11120 Belgrade 35, Serbia, avencl@mas.bg.ac.rs

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ABSTRACT:
Using of Al-alloys for producing of engine cylinders and blocks, instead of gray cast iron, results with weight savings and lower fuel consumption and therefore reduced pollution. One of the possible solutions for overcoming of poor Al-alloys tribological properties is the deposition of coating with thermal spray technology. In this paper, the basic characteristics (structure, hardness and tensile bond strength) and tribological properties of two types of ferrous-based coatings were analysed and compared with gray cast iron as a standard material for cylinder blocks. Process used for coating deposition on an Al-Si alloy substrate was Atmospheric Plasma Spraying (APS). The pin-on-disc tribometer was used to carry out these tests under dry sliding conditions, sliding speed of 1 m/s, sliding distance of 5000 m and different normal loads. Tribological test results showed that, for the investigated conditions, both coatings had improved wear resistance and lower friction coefficient compared to the gray cast iron.

Keywords: *Atmospheric plasma spraying, ferrous-based coatings, friction, wear.*

SAŽETAK:
Korištenje aluminijskih legura kao zamjene za cilindarske košuljice i blokove motora od sivog lijeva rezultira smanjenjem mase cijelog vozila, uštedama u potrošnji goriva i smanjenju emisije štetnih plinova. Jedno od mogućih rješenja za prevladavanje loših triboloških karakteristika aluminijskih legura je primjena nekog od postupaka termičkog nanošenja prevlaka raspršivanjem. U ovom radu je dana analiza osnovnih karakteristika (mikrostruktura, tvrdoća i zatezna čvrstoća veze) dvije prevlake na bazi željeza nanesene na Al-Si leguru plazma sprej postupkom u atmosferskim uvjetima. Tribološke karakteristike ovih prevlaka su ispitane i uspoređene sa sivim lijevanim željezom, standardnim materijalom za izradu košuljica i blokova motora. Za tribološka ispitivanja u uvjetima klizanja bez podmazivanja korišten je tribometar tipa epruveta na disku, a ostali uvjeti ispitivanja su bili slijedeći: brzina klizanja 1 m / s, put klizanja 5000 mi više različitih normalnih opterećenja. Rezultati pokazuju da, za date uvjete ispitivanja, obje prevlake imaju veću otpornost na trošenje i niži koeficijent trenja u odnosu na referentni materijal.

Ključne riječi: *Plazma sprej postupak u atmosferskim uvjetima, prevlake na bazi željeza, trošenje.*

1. Introduction

Aluminium alloys have attractive physical and mechanical properties. They are lightweight, low costs production (with sand casting technology), easy to machine and have good recycling possibilities (up to 95 %) [1]. Due to these facts their application in automotive and other industries increases. One of the applications in automotive industry is replacing of material for engine cylinder blocks, which has been traditionally made entirely of gray cast iron. This is quite understandable since the major mechanical power losses in internal combustion engines occur in the cylinder-piston system (nearly the 45 % of all losses) [2].

Use of Al alloys as a substitution for engine cylinder blocks made of grey cast iron, has positive aspects such as reduction of engine mass, lower fuel consumption and therefore reduced pollution. Unfortunately, most aluminium alloys, especially those suitable for mass production from the technological-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 at least such tribological properties like those of grey cast iron or even better ones. Because of this, the surface engineering of the engine cylinder bores is in the focus of most producers of aluminium alloy internal combustion engines [3-5].

One of the frequently applied method to improve tribological characteristics of aluminium alloys is using of coatings. Currently most predominant surface treatments are chemical treatments and thermal spray coatings. Chemical treatments like electroplating of chromium and nickel coatings are becoming increasingly threatened by environmental regulation. Moreover, one should prevent microscopic particles of chromium and nickel, a health hazard, from entering the environment through the exhaust pipe. This process requires complex chemistry and is relatively expensive. Thermal spray coatings are relatively new solution for cylinder bore protection and plasma spray process is the only industrially commercialised one. Comparison of mentioned solutions for overcoming of poor Al alloys tribological properties shows advantages and better characteristics of plasma coatings in many criteria like engine size and weight, friction between rings and liner, engine oil consumption, resistance to acids, environmental impact, production costs etc. [6]. Size and weight of engine blocks can be significantly decreased using of internal plasma spray technology, in comparison with the traditional cast iron liners [7]. The coefficient of friction between piston rings and cylinder, as well as, wear of both elements can be significantly reduced [8,9].

In this paper the tribological properties under dry sliding conditions of two types of ferrous-based coatings, deposited by Atmospheric plasma spraying (APS) on Al-Si alloy substrate, were analysed and compared with gray cast iron as a standard material for cylinder blocks.

2. Materials and procedure

2.1 Materials

Substrate material was Al-Si cast alloy (EN AlSi10Mg), with the following chemical composition: Al-9.8Si-0.48Fe-0.1Cu-0.2Mn-0.3Mg-0.08Zn-0.05Ti (wt. %). It was fabricated using send casting, followed with solution annealing at 540 °C with 35 °C/h, water quenching and artificial ageing at 160±5 °C for 6 h.

Two spray powders were used in this experiment “Metco 92F” and “Sulzer Metco 4052”, ref. as 92F and 4052. The chemical compositions of the powders are shown in Table 1. The powder size (diameter) was between: 10 and 53 μm for powder 92F and 15 and 38 μm for powder 4052. Coatings deposition was done with Atmospheric Plasma Spraying (APS). Details of the technology process and spray conditions were described elsewhere [10]. Coating thickness after the machining was 100 µm for coating 92F and 170 µm for coating 4052. A gray cast iron was chosen as a standard material to compare its performances with the coatings. The chemical composition of this material, fabricated using the sand casting procedure followed with heating at 550 °C in order to eliminate residual stress in the material, is shown in Table 1.

Table 1. Chemical composition of used powders and gray cast iron

Powder / material	Element, wt. %						
	C	Si	Mn	P	Cr	Ni	Fe
92F	3.5	–	0.35	–	–	–	Balance
4052	1.2	–	1.5	–	1.3	0.3	Balance
Gray cast iron	3.18	2.17	0.60	0.7	0.37	–	Balance

The microstructure of test materials was analysed with optical microscope (OM), where the coatings were sectioned perpendicular to the coated surface. Phases that were present in the coatings were analysed by X-ray diffraction (XRD). After an identification of oxides, their volume fraction, as well as porosity, presence of cracks and unmelted particles, their percentage share were measured. Characterisation was done according to the Pratt & Whitney standard [11]. In boat coatings, elongated splats of molten powder form a lamellar structure, with oxide layers in between, typical for spray coatings (Fig. 1). No cracking was found in the coatings and no peeling was observed at the interface between the coating and the substrate.

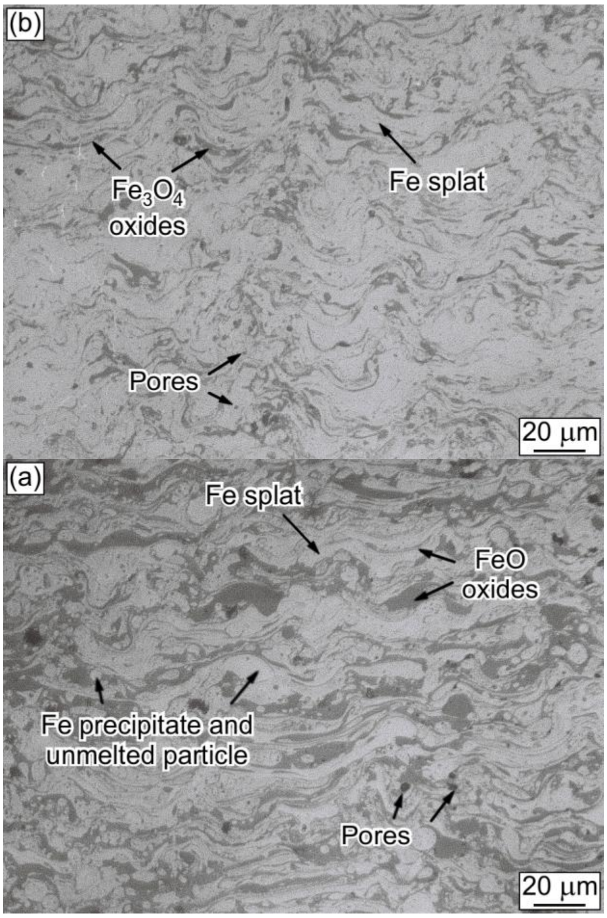

Figure 1. OM cross-section micrograph of: (a) coating 92F and (b) coating 4052

The X-ray diffraction (XRD) analysis revealed that coating 92F structure consists of elemental iron (Fe) and magnetite (Fe_3O_4), while coating 4052 contains elemental iron (Fe) and wustite (FeO). Other phases are present in a small amount, less then 3 %. Oxide content for coating 92F was approximately 13 % and porosity was 2.3 %. Presence of unmelted particles and precipitates was not detected in this coating. Oxide content for coating 4052 was around 41 % and porosity was 5.8 %, with the pores of irregular shape. It must be mentioned that porosity of the coating 4052 was detected in areas with unmelted particles (Fig. 1b). Volume fraction of unmelted particles and precipitates in this coating was approximately 10 %.

Tensile bond strength tests were performed on a hydraulic tensile test rig using a crosshead speed of 0.5 mm/min, for all the tests. The bond strength was calculated by dividing the failure load by the cross-sectional area of the specimen. The geometry of the specimens and testing procedure was according to ASTM C633 standard [12]. Hardness was measured using a Vickers hardness tester under a 10 kg load, and the microhardness was measured under a 100 g load using a micro-Vickers hardness tester. The presented results of the testing of tensile bond strength as well as hardness of tested materials represent an average value of a larger number of tests (Table 2).

Table 2. Tensile bond strength and hardness of tested materials

Material	Tensile bond strength, MPa	Hardness, HV_{10}	Microhardness, $HV_{0.1}$
Gray cast iron	–	254	329
Coating 92F	31.08	–	495
Coating 4052	32.91	–	390

2.2 Tribological tests procedure

Tribological tests were carried out on the pin-on-disc tribometer under dry sliding conditions, in ambient air at room temperature (≈ 25 °C). Cylindrical pins of tested materials having 2.5 mm diameter and 30 mm length were used as wear test samples. Disc (hereafter referred to as counter body) of 100 mm diameter and 10 mm thickness was made of nodular gray cast iron (220 HV_{10} and 238 $HV_{0.1}$). This material was chosen as a standard piston ring material with specification according to the ISO standard (Subclass Code MC 53) [13]. Diagram of the load, pin, disc and the direction of the rotation is shown in Figure 2. Surface roughness of pins and the counter body was approximately R_a = 0.5 and 0.3 μm, respectively.

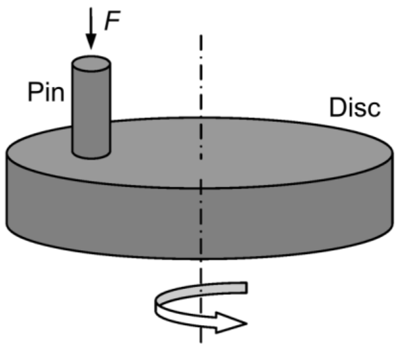

Figure 2. Schematic diagram of the pin-on-disc tribometer

Before and after testing, both the pin and the counter body (disc) were degreased and cleaned with benzene. Pins were weighed with accuracy of 10^{-4} g before and after each test to calculate the mass loss. The value of friction force was monitored during the test and through data acquisition system stored in the PC, enabling the calculation of friction coefficient. Tests were carried out at selected test conditions: constant sliding speed of 1 m/s, constant sliding distance of 5000 m and normal load of 5 / 10 / 15 / 20 and 25 N. Taking into account the contact area of approximately 5 mm^2 the specific load was 1 / 2 / 3 / 4 and 5 MPa, respectively. After testing, worn surfaces of pins and wear products were examined with scanning electron microscopy (SEM).

3. Results and discussion

In order to achieve a higher confidence level in evaluating test results, three or more replicate tests were run for all the tested materials. The results indicate good reproducibility of the wear and friction results.

The wear rates (calculated for the steady state period) of tested materials at different specific loads are presented in Figure 3. Tendency for all materials was the same, i.e. with the increase of specific load the wear rate also increases. The highest wear rates, for the whole applied load interval, had gray cast iron, then coating 92F and at the end coating 4052. Presence of the critical load at which the wear rate abruptly increases, indicating the transition of the wear regime, was noticed for all tested materials. Values of this critical load were different for the tested materials. For both coatings they were higher than the value for the gray cast iron, which is certainly an advantage of these materials.

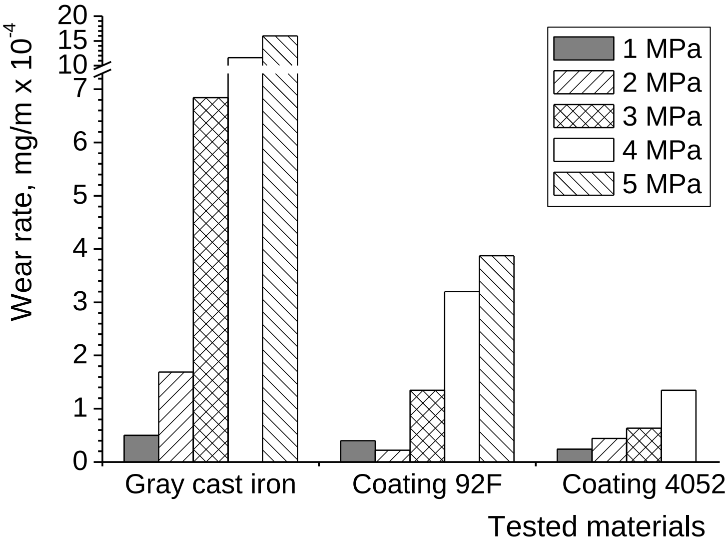

Figure 3. Wear rates of the tested materials for different specific loads

Possibility of the gray cast iron substitution with the two tested coatings, from the aspect of adhesion wear resistance, could be analysed from Figure 3. For the whole applied load interval both coatings had lower wear rates which indicate that they could be adequate substitutions. In addition to this, condition of pin contact surfaces was observed during these tests as well as at the end of them. There was not noticed any plastic deformation of the tested material, for the whole applied load interval. The values of the applied loads were similar to the average values that occur in cylinders of the gasoline internal combustion engines, compressors and other piston machines. Good load bearing characteristics of gray cast iron was expected since it is a standard material for cylinder blocks. For the both coatings it could be concluded that they also satisfy load bearing capacity criteria, and could be a possible substitution for gray cast iron.

The coefficient of friction values did not change significantly with the change of specific load and one mean value per material could be accepted for the whole applied load interval. An average values (for different specific load) of the steady state coefficient of friction for the tested materials were as follows: gray cast iron ($\mu = 0.53$), coating 92F ($\mu = 0.49$) and coating 4052 ($\mu = 0.37$). Attained friction coefficient values of the gray cast iron and both coatings were in expected range for metals in dry sliding conditions. Both coatings had lower values of the coefficient of friction than the gray cast iron, principally because their higher hardness values (see Table 2). The highest coefficient of friction values was for gray cast iron, then for coating 92F, while coating 4052 showed the lowest values of coefficient of friction, which also indicates that both coatings could be possible substitution for the gray cast iron.

After the visual inspection, analysis of the worn surfaces was performed with SEM. Worn surfaces analysis showed that the dominant wear mechanism was adhesion, with others mechanisms: oxidation, abrasion and delamination as minor ones. SEM micrographs of pins worn surfaces at the end of tests are presented in Figures 4 and 5. At lower specific loads (1 and 2 MPa) gray cast iron pins surface was not in full contact with the counter body. Basic lamellar structure of the material that has been exposed to the ultra mild wear could be clearly noticed (Fig. 4a). At higher specific loads (3 and 4 MPa) more intensive, abrasive wear starts, and at highest specific load of 5 MPa adhesive wear occurs due to the presence of high pressures and contact temperatures (Fig. 4b).

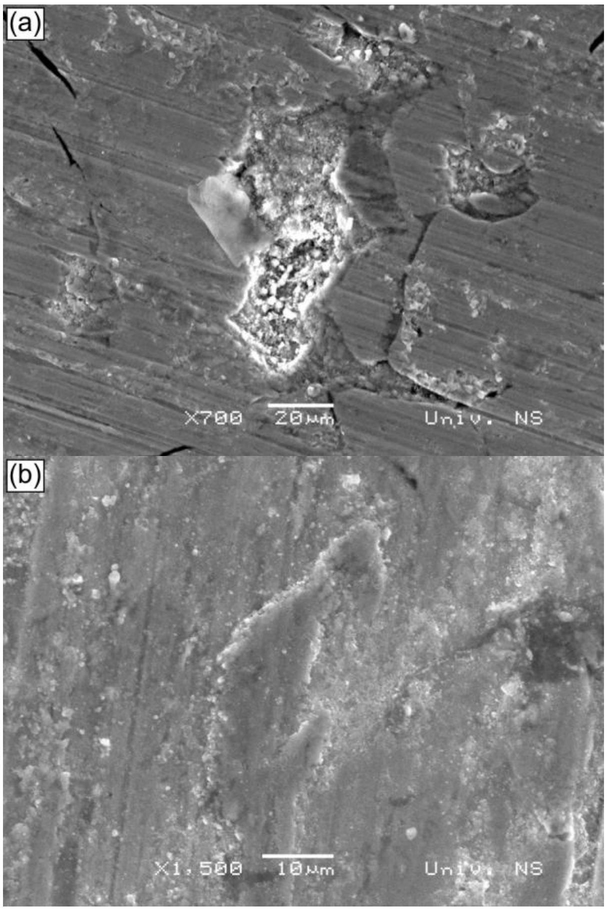

Figure 4. SEM micrographs of the pins worn surfaces: (a) gray cast iron at 2 MPa and (b) gray cast iron at 5 MPa

Worn surfaces of both coatings showed similar appearance. At lower specific loads (1 and 2 MPa) presence of the transferred counter body material to the pin surfaces could be noticed (Fig. 5a). This transferred material was in form of plates that fractures under the load and brakes into small pieces, that have been detected in wear products. At specific load of 3 MPa ploughing and adhesive wear occur, while at highest specific load of 4 MPa adhesion was dominant wear mechanism and adhesive wear pits with accumulated wear products could be noticed (Fig. 5b). Total area of this adhesive wear pits was around 20 % and the basic structure of the coatings around pits is still visible, which indicates that the wear was not intensive.

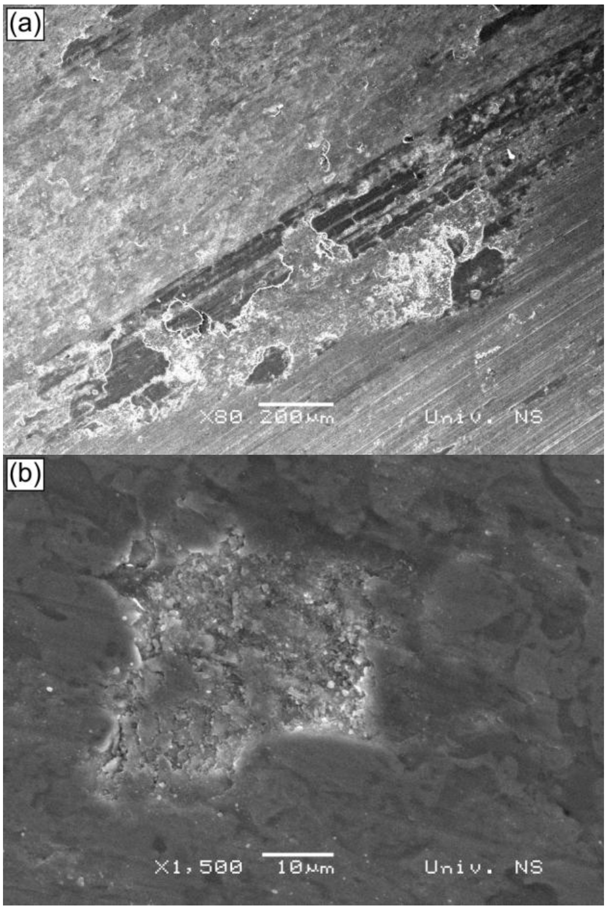

Figure 5. SEM micrographs of the pins worn surfaces: (a) coating 92F at 2 MPa and (b) coating 4052 at 4 MPa

Wear products were also collected during the tests and photographed with SEM. Products generated by the wear of the materials in contact (counter body and corresponding pin) originate mostly from the pin material. Morphology and size of wear products for all tested materials were similar. Mainly sharp edge, plate-like particles prevail, without any visible grooves on them, which is characteristic for the adhesive wear.

4. Conclusion

Tribological test results showed that, for the investigated conditions, both coatings had improved wear resistance and lower friction coefficient compared with gray cast iron.

Both coatings also satisfy load bearing capacity criteria that usually occur in standard piston machines, and could be an adequate substitution for gray cast iron as a standard material for cylinder blocks.

Wear mechanisms analysis showed that the dominant wear mechanism was adhesion, with others mechanisms: oxidation, abrasion and delamination as minor ones.

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