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TRIBOLOGICAL PROPERTIES OF A356 Al-Si ALLOY BASE COMPOSITE REINFORCED WITH AL_2O_3 PARTICLES (MMC)

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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 [2-6]. 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. 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 [7-9].

One of the methods applied to improve tribological characteristics of aluminium alloys is using of different types of metal matrix composites (MMCs). The idea that relatively small amount of reinforcement can improve characteristic of matrix material by several times is very interesting, so constant improvements of MMCs process technologies and possibilities for their new application are not a surprise. 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.

In this paper the tribological properties under dry sliding conditions of two Al-MMCs, reinforced with Al_2O_3 particles (10 wt. %, 12 and 35 μm), were analysed and compared with gray cast iron as a standard material for cylinder blocks.

Experimental

The matrix material was A356 hypoeutectic Al-Si alloy (EN AlSi7Mg0.3) with the following chemical composition (in wt. %): Al-7.2Si-0.02Cu-0.29Mg-0.01Mn-0.18Fe-0.01Zn-0.02Ni-0.11Ti.

Composites were produced by the compocasting process using mechanical mixing of the matrix, i.e. Al_2O_3 particles as reinforcement were added into the semi-solid A356 alloy by infiltration and admixing. The average size of Al_2O_3 particles was 12 μm and 35 μm, whereas the amount of particles was 10 wt. %. Experimental procedure and apparatus used for the compocasting processing are described and discussed elsewhere [10].

Three sets of specimens were used for testing: two was fabricated from the composite material with 12 and 35 μm particles size (referred as 10-12 and 10-35, respectively), and the third was fabricated from the gray cast iron (ref. as SL 26). A gray cast iron was chosen as a standard material to compare its performances with the composites.

Composite specimens were subjected to heat treatment with following parameters: solution annealing at 540 °C for 6 h, water quenching and artificial aging at 160 °C for 6 h. The chemical composition of gray cast iron, fabricated using the sand casting procedure followed with heating at 550 °C in order to eliminate residual stress in the material, was: Fe-3.18C-2.17Si-0.60Mn-0.7P-0.37Cr.

Microstructural and mechanical characterization of tested materials included metallographic examinations with optical microscope (OM) and hardness measurements. Metallographic samples were prepared in a standard way applying grinding and polishing, whereas etching in Keller's solution (the mixture of 95 ml H_2O, 2.5 ml HNO_3, 1.5 ml HCl and 1 ml HF) was used to reveal the microstructure. Hardness measurements were carried out using a Vickers diamond pyramid indenter and 10 kg load. Density of the specimens was measured by Archimedes method.

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) [11]. Diagram of the load, pin, disc and the direction of the rotation and the photography of tribometer are shown in Fig. 1. Surface roughness of pins and the counter body was approximately $R_a = 0.5$ and 0.3 μm, respectively.

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.

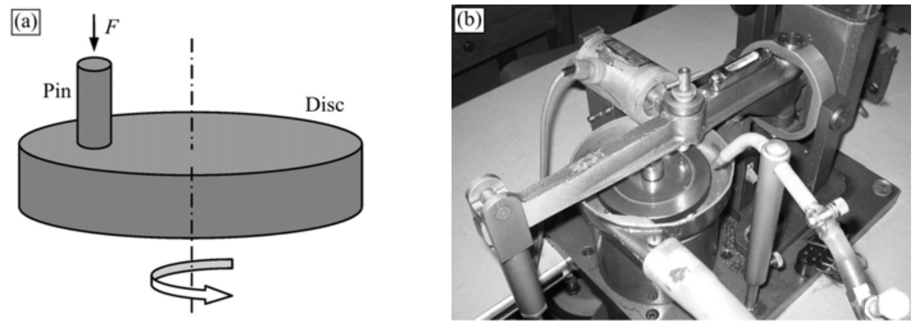

Fig. 1: Pin-on-disc tribometer: (a) schematic diagram and (b) photography

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 and 20 N. Taking into account the contact area of approximately 5 mm^2 the specific load was 1 / 2 / 3 and 4 MPa, respectively. After testing, worn surfaces of pins and wear products were examined with scanning electron microscopy (SEM).

Results and Discussion

The results of metallographic investigation of the matrix alloy and composites are illustrated in Fig. 2. The microstructure of the matrix alloy consists of fully dendritic primary α phase and a eutectic in interdentritic area (Fig. 2a). Compocasting process produced morphological changes in the microstructure, i.e. the microstructure of composites is distinguished by large primary α phase rosettes (Fig. 2b and 2). Significant coarsening of the α phase occurred during compocasting. Al_2O_3 particles reinforcement are visible not only in the eutectic zone but are infiltrated in the α phase primary particles as well.

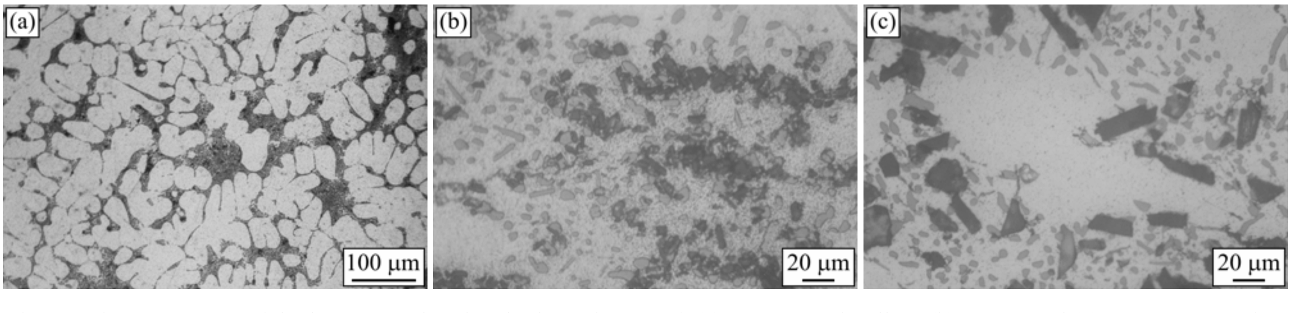

Fig. 2: Microstructures of the heat treated and etched specimens of: (a) A356 matrix alloy, (b) 10-12 and (c) 10-35 composites

The values of hardness were 73,41, 106,85 and 254 HV_{10} for 10-12, 10-35 and SL 26 material, respectively, while the density of tested materials were 2.66, 2.71 and 7.22 g/cm^3 for 10-12, 10-35 and SL 26, respectively. At least six measurements were made for each specimen in order to eliminate possible segregation effects and to get a representative values.

In order to achieve a higher confidence level in evaluating tribology 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 Fig. 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 SL 26, then composite 10-12 and at the end composite 10-35. The influence of the reinforcement particle size on the wear properties of composite materials is dual and depends on the specific load and the sliding speed. In most of the cases at lower loads and higher speeds increase of the particle size induce lower wear rates, while at higher loads and lower speeds increase of the particle size has negative influence, i.e. increase wear rate [12]. Similar influence of the reinforcement size on the wear rate occurs for tested composite materials 10-12 and 10-35 (Fig. 3).

Possibility of the gray cast iron (SL 26) substitution with the two tested coatings, from the aspect of adhesion wear resistance, is shown in the form of log-log scale diagram (Fig. 4). Wear rate dependence on the specific load for the gray cast iron is represented with two straight lines that divide the diagram into two fields: field of the materials that could and that could not be adequate substitution for the gray cast iron. Comparison of the tested materials, by the wear resistance, shows that both coatings belong to the possible substitution field.

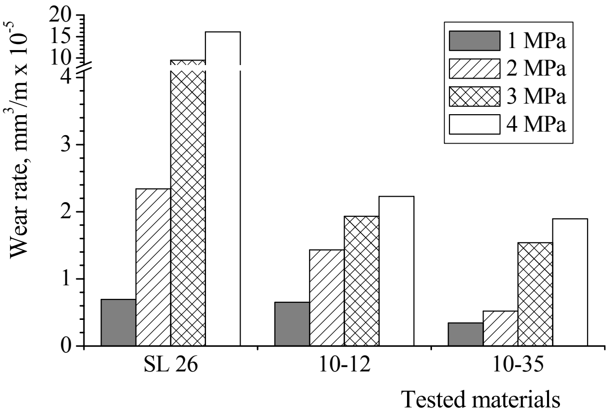

Fig. 3: Wear rates of the tested materials for different specific loads

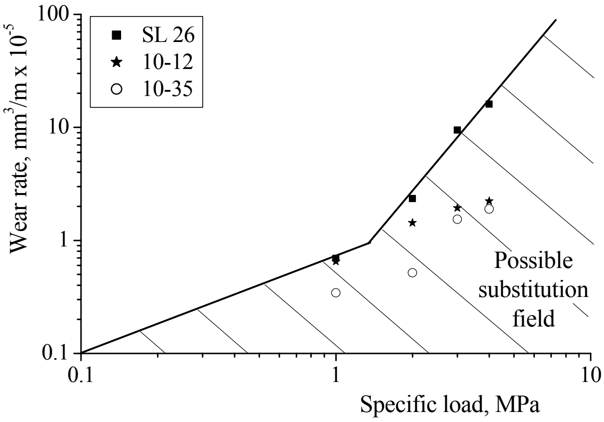

Fig. 4: Wear rate vs. specific load

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: SL 26 ($\mu = 0.53$), composite 10-12 ($\mu = 0.61$) and composite 10-35 ($\mu = 0.60$).

Attained friction coefficient values of the gray cast iron and both coatings were in expected range for metals in dry sliding conditions. Both composite materials had higher values of the coefficient of friction than the gray cast iron (SL 26), principally due to the presence of hard reinforcing particles, but the values was in accepted range and both composites could be accepted as a possible substitution for the gray cast iron.

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 SL 26 material, for the whole applied load interval, while for the both composites there was lightly pronounced plastic flow of material on pin surface. For the composite 10-12 that plastic flow was minimal and occurred at highest applied specific load (4 MPa), while for the composite 10-35 it starts at 3 MPa and become more pronounced at 4 MPa. 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 composites it could be concluded that they also satisfy load bearing capacity criteria, and could be a possible substitution for gray cast iron if specific loads are below 3 – 4 MPa.

After the visual inspection, analysis of the worn surfaces was performed with scanning electron microscopy (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 Fig. 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. 5a). At higher specific loads more intensive, abrasive wear starts, and also adhesive wear occurs due to the presence of high pressures and contact temperatures.

Worn surfaces of both composite materials 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. 5b). 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. Formation of deep caverns could also be noticed (denoted by arrows in Fig. 5b). At higher specific loads presence of deep caverns could still be noticed, but less pronounced and adhesion was the dominant wear mechanism. For composite 10-35 plastic flow of material could be observed for the highest specific load of 4 MPa (Fig. 5c).

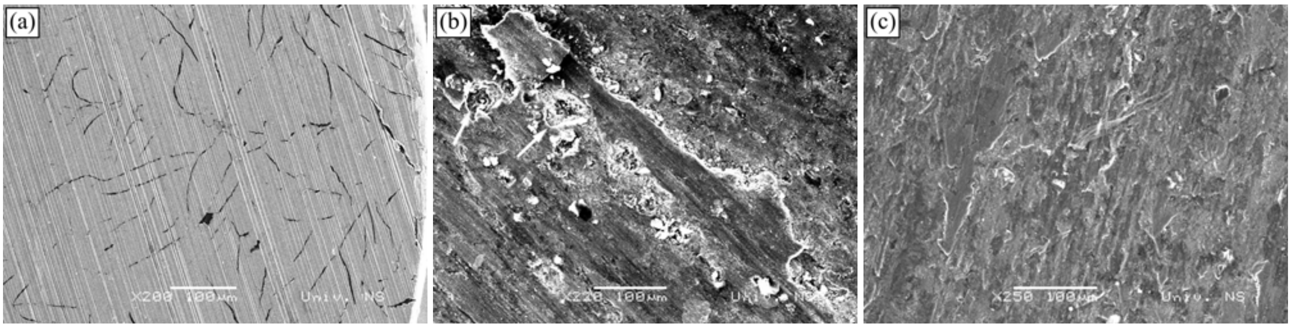

Fig. 5: SEM micrographs of the pins worn surfaces: (a) SL 26 material at 1 MPa, (b) composite 10-12 at 1 MPa and (c) composite 10-35 at 4 MPa

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.

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