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Tribological properties of thixocasted and heat-treated hypoeutectic Al-Si alloy A356

K e y w o r d s

Al-Si alloy, thixocasting, dry and lubricated sliding condition, wear, friction.

S ł o w a k l u c z o w e

Stop Al-Si, tarcie suche, smarowanie, zużycie, tarcie.

S u m m a r y

This paper presents results of structural, mechanical and tribological tests of thixocasted and heat-treated hypoeutectic Al-Si alloy A356 (EN-Al Si7Mg0.3). The results of tribological tests were analysed and compared with the results of grey cast iron, which was chose as a standard material for cylinder blocks. The pin-on-disc tribometer was used to carry out tribological tests under dry and lubricated sliding conditions at different loads and speeds. The results showed that thixocasted and heat-treated Al-Si alloy under dry sliding conditions, for applied loads interval, could not be satisfactorily used since plastic flow of the material occurs. However, under lubricated sliding conditions tested material showed a low coefficient of friction without any plastic deformation.

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1. Introduction

The use of light alloys in the transport industry is becoming a stringent need, because weight saving is one of the most important target in new vehicles design. Cast aluminium-silicon (Al-Si) alloys are widely used for the production of various automotive components, since silicon is one of a few alloying elements that does not increase the density of aluminium alloys. Aluminium alloys with moderate silicon levels, like A356, are typically used. Unfortunately, these alloys have their shortcomings that reflected, first of all, in inappropriate tribological properties of these materials. New production technologies, like thixocasting, are one of the possible solutions [1-4]. Additionally, the heat treatment to the T6 condition improves the wear resistance due to the higher material hardness [5].

As far as thixocasted Al-Si alloys are concerned, their improved mechanical properties over conventionally cast Al-Si alloys have been proven in many studies [6-8], while only a few studies dealing with tribological properties of thixocasted Al-Si alloys have been undertaken. Kang and Jung [4] showed that wear resistance of a thixoformed hypoeutectic Al-Si alloy could be very similar to cast iron if appropriate process parameters are used. Lasa and Rodriguez-Ibabe [9] also investigated two hypoeutectic Al-Si alloys produced with thihoforming and they found improvements of wear behaviour compared to the similar alloys cast in conventional metallic moulds. This was attributed to the fine, homogeneous, globular microstructure and the smaller spacing of the primary silicon particles in thihoformed alloys. Improvements of wear behaviour gained with additional heat treatment of thixocasted Al-Si alloys were explained with the improvements of their mechanical properties.

This paper presents the results of structural, mechanical and tribological tests of thixocasted and heat-treated hypoeutectic Al-Si alloy A356 (EN-Al Si7Mg0.3). The results of tribological tests, under dry and lubricated sliding conditions, were analysed and compared with the results of grey cast iron, which was chosen as a standard material for cylinder blocks.

2. Experimental procedure

2.1. Materials and heat treatments

Two sets of test specimens were used in this investigation. The first of test specimens was made of thixocasted and heat-treated hypoeutectic Al-Si alloy A356 (EN AlSi7Mg0.3), ref. as Thixo T6. According to the thixocasting procedure the A356 alloy was first obtained in the form of cylindrical billets, through magnetohydrodynamic (MHD) stirring and casting. MHD stirring involves electromagnetically stirring of the alloy in the semi-solid state, in order to break up the existing dendrites. After that, the billets were additionally heated up (to app. 580°C), then placed in a high-pressure die casting press, and injected (at 210 MPa) directly into the die (preheated at 200 to 250°C). All thixocasted specimens were heat treated with a variant of the commercial heat treatment (T6). It consisted of a solution annealing at 548ºC during 6 hours, followed by water quenching and artificial ageing at 160ºC during 6 hours, which was also followed by water quenching.

The second set of test specimens was made of grey cast iron (ref. as SL 26) with the following chemical composition (in wt. %): Fe-3.18C-2.17Si-0.60Mn-0.7P-0.37Cr. A grey cast iron was chosen as a standard material to compare its performances with the thixocasted and heat-treated A356 alloy. The specimens made from SL 26 were fabricated using the sand casting procedure followed with heating at 550°C in order to eliminate residual stress in the material.

2.2. Structural and mechanical examinations

Microstructural and mechanical characterisation of tested materials included metallographic examinations with optical microscope (OM) and hardness and density 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 a 10 kg load. Density of the samples was measured by Archimedes method.

2.3. Tribological tests

Tribological tests were carried out on the pin-on-disc tribometer under dry and lubricated 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 test samples. Disc (hereafter referred to as counter body) of 100 mm diameter and 10 mm thickness was made of nodular grey cast iron (220 HV 10). This material was chosen as a standard piston ring material with specification according to the ISO standard (Subclass Code MC 53) [10]. Surface roughness of pins and the counter body was approximately $R_a = 0.5$ and 0.3 μm, respectively.

For dry sliding condition tests, before and after testing, both the pin and the counter body were degreased and cleaned with benzene. Pins were weighed with an 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 5 different normal loads. Taking into account the contact area of approximately 5 mm^2, the specific load (in MPa) was calculated as normal load divided with contact area.

For lubricated sliding condition tests standard motor oil was used (ACEA E3, SAE 15W-40). The temperature of oil was monitored and maintained constant at 60 °C during the tests. Only the value of friction force was monitored during the lubricated sliding condition tests. Normal load was constant and had the value of 30 N, i.e. 6 MPa. The value of sliding speed was varied from 0.22 to 4.62 m/s (all together 12 different values), while the test duration was constant (15 minutes). Test duration was selected according to the pre-tests, in order to provide steady-state values of friction coefficient.

3. Results and discussion

3.1. Structural and mechanical examinations

The results of metallographic investigation of the thixocasted and heat--treated Al-Si alloy (Thixo T6) are illustrated in Fig. 1. The microstructure of Thixo T6 consists mainly of elliptical, aluminium rich, primary particles. During heat treatment, primary particles became larger and the entrapment of an eutectic phase within the primary particles took place (Fig. 1a). Silicon particles appeared as elliptical nodules (with a size 1.5 – 5 μm) and large irregular plates, statistically distributed in eutectic phase among large primary aluminium particles (Fig. 1b), and in the form of rows and clusters (details A and B in Fig. 1b), at rosette parts boundaries.

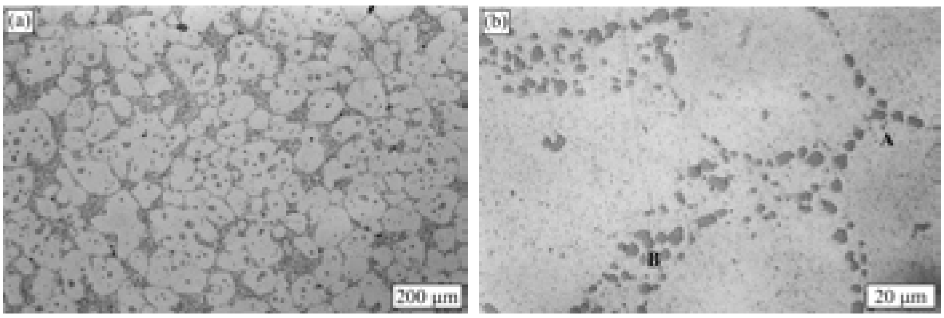

Fig. 1. OM microphotograph of etched Thixo T6 microstructure

The values of hardness were 121 and 254 HV 10 for Thixo T6 and SL 26 material, respectively, while the density of tested materials were 2.70 and 7.22 g/cm^3 for Thixo T6 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.

3.2. Tribological tests

In order to achieve a higher confidence level in evaluating dry sliding conditions test results, three or more replicate tests were run for all the tested materials. The results indicate good repeatability of the wear and friction results. Obtained results of the tested materials mass loss, for different specific loads, are shown as a function of sliding distance in the form of the comparative wear curves (Fig. 2). Wear curves were formed with the following method: the mass of all cylindrical pins was measured at the beginning of the test and at each pause in the testing (after 250, 500, 1000, 2000, 3000, 4000 and 5000 m), so the mass loss could be calculated for the mentioned sliding distances.

The wear curves of tested materials were in correlation with the theoretical ones. The amount of worn material increased with increasing of the specific load. From the shape of the wear curves it could be noticed that the run-in period was very short or did not exist at all. Almost from the beginning of the tests there was a steady-state wear in which the dependence of the mass loss from the sliding distance could be approximated as linear.

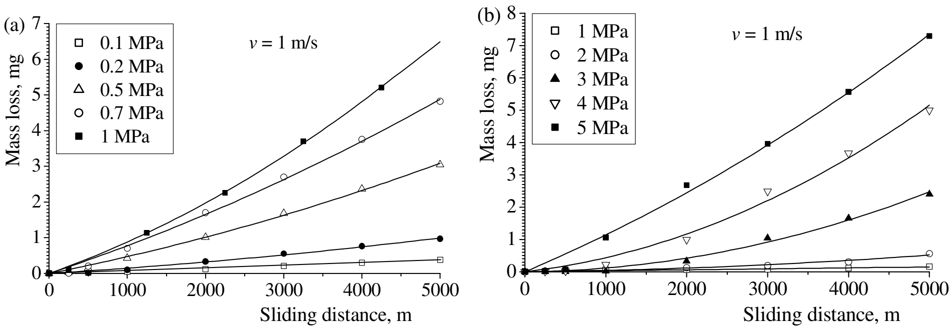

Fig. 2. The wear curves of: a) Thixo T6 material and b) SL 26 material

The wear rates (calculated for the steady-state period) of tested materials at different specific loads are presented in Fig. 3. The tendency for all materials was the same, i.e. with the increase of specific load the wear rate also increases. The Thixo T6 showed significantly higher wear rates than SL 26, almost two orders of magnitude (Fig. 3a).

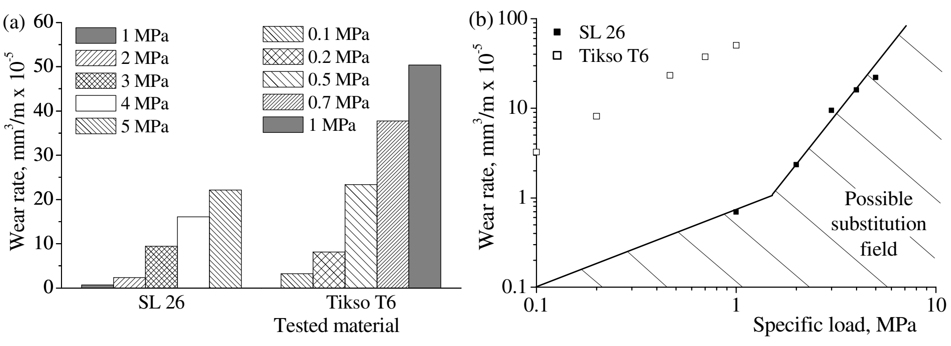

Fig. 3. The wear rates of tested materials for different specific loads

Presence of the critical load at which the wear rate abruptly increases, indicating the transition of wear regime, was noticed for SL 26 material. The possibility of grey cast iron (SL 26) substitution with Thixo T6 material, from the aspect of adhesion wear resistance, is shown in the form of log-log scale diagram (Fig. 3b). The dependence of the wear rate from the specific load for the grey 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 grey cast iron. From Fig. 3b, it can be noticed that Thixo T6 did not enter the possible substitution field.

The coefficient of friction values of tested materials 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. The values of coefficient of friction were 0.32 and 0.53 for Thixo T6 and SL 26 material, respectively. The attained friction coefficient value of the grey cast iron was in expected range for metals in dry sliding conditions. The relatively low friction coefficient value of the Thixo T6 material is due to the fact that at applied specific load pin surfaces of this material start to deform plastically and to flow (this was confirmed with optical observation, Fig. 4a).

Condition of pin contact surfaces was observed during the tests as well as at the end of tests and recorded with a camera (Fig. 4). Plastic flow of material on the surface of some pins was noticed. This plastic flow at Thixo T6 material was present, more or less intensive depending on the specific load, for the whole applied load interval (Fig. 4a), except for the lowest applied load of 0.1 MPa. For the SL 26 material, there was no noticed plastic deformation, for the whole applied load interval, even for the highest applied load of 5 MPa (Fig. 4b).

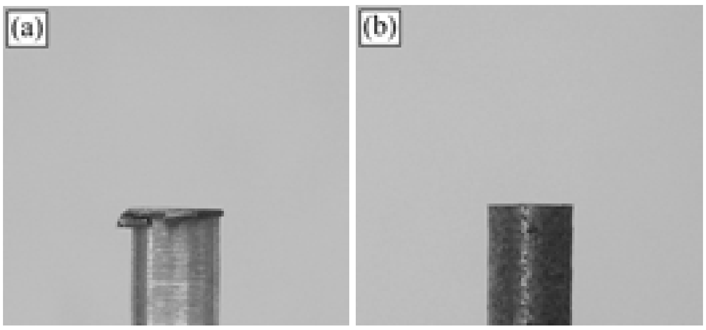

Fig. 4. The appearance of the pin contact surface of tested materials at the end of testing: a) Thixo T6 at 0.7 MPa and b) SL 26 at 5 MPa

The values of applied loads for SL 26 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 grey cast iron was expected, since it is a standard material for cylinder blocks.

Tribological tests in lubricated sliding conditions were additionally done, in order to simulate the working condition in cylinders of the gasoline internal combustion engines, compressors, and other piston machines. The parameters that were taken into account were normal load, sliding speed, and lubricant type and temperature. The obtained dependence of the friction coefficient from sliding speed, for tested materials, is shown in Fig. 5.

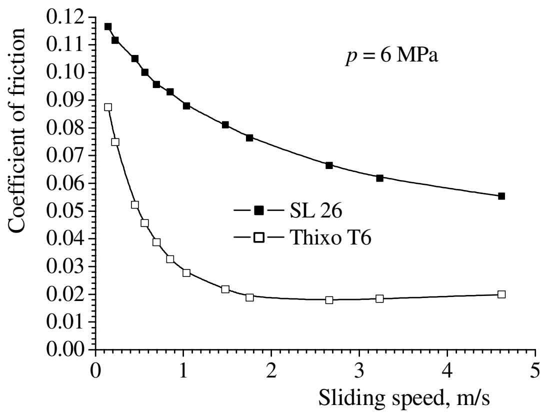

Fig. 5. Dependence of the friction coefficient from the sliding speed, for tested materials

The obtained values of the coefficient of friction indicate that a boundary lubrication condition was maintained. From Fig. 5, it can be noticed that, for investigated conditions, for SL 26 material, the coefficient of friction decreases with the increase of sliding speeds, while, for Thixo T6 material, the coefficient of friction decreased up to the value of the sliding speed of app. 3 m/s, and than it starts to increase with the increase of sliding speed. This was in accordance with the Stribeck curve. For all applied sliding speeds, the value of the friction coefficient was lower for Thixo T6 than for SL 26 material. Visual inspection of samples did not show any plastic deformation on either of the tested materials.

Obtained results suggest that, from the aspect of friction in lubricated sliding condition, Thixo T6 material could be an adequate substitution for grey cast iron (SL 26) in cylinders of the piston machines. Since these tests were just initial, further investigation should be done in a reciprocating sliding lubricated condition, with wear measurements as well.

4. Conclusion

Grey cast iron was chosen as a standard material for cylinders of the gasoline internal combustion engines, compressors, and other piston machines. In order to find an adequate substitution for grey cast iron, the structural, mechanical and tribological properties of thixocasted and heat-treated hypoeutectic Al-Si alloy A356 was investigated.

The results of tribological tests under dry sliding conditions showed that the wear rates of the thixocasted and heat treated Al-Si alloy were almost two orders of magnitude higher than that of grey cast iron. Also, Al-Si alloy did not satisfy load bearing capacity criteria for the investigated load interval, and plastic flow of the material occurs. These results indicate that investigated Al-Si alloy has low adhesion wear resistance and could not be used for the same purposes, in dry sliding condition, as grey cast iron.

On the other side, under lubricated sliding conditions, when boundary lubrication was achieved, thixocasted and heat-treated Al-Si alloy showed comparable characteristics with grey cast iron. The coefficient of friction was lower and no plastic deformation occurs, i.e. these preliminary results indicate that investigated Al-Si alloy could be a possible substitution for grey cast iron in boundary lubrication conditions.

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Własności tribologiczne stopu Al-Si A356 po obróbce cieplnej

S t r e s z c z e n i e

Przedstawiono wyniki badań strukturalnych, mechanicznych i tribologicznych stopu hipoeutektycznego Al-Si A356 (EN-AlSi7 Mg0,3). Wyniki testów tribologicznych zostały porównane z rezultatami uzyskanymi dla żeliwa szarego. W testach użyto stanowiska badawczego typu trzpień–tarcza. Badania obejmowały styk smarowany i niesmarowany dla szeregu wartości obciążenia i prędkości. Stwierdzono, że bez smarowania badany stop nie wykazuje pozytywnych własności z powodu występujących odkształceń plastycznych.

W styku smarowanym badany stop wykazał niski współczynnik tarcia i brak odkształceń plastycznych.