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INFLUENCE OF GRAPHITE MACROPARTICLES ON FRICTION AND WEAR OF A356/SiC/Gr COMPOSITES IN LUBRICATED CONDITIONS

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Abstract: *Metal matrix composites (MMCs) with Al-Si alloy bases and ceramic reinforcements are extensively used in tribological applications such as automotive pistons, cylinder blocks, plain bearings and others where boundary lubrication conditions may occur. In those conditions, intensive adhesive wear (due to the seizure of the Al-Si alloy) and abrasive wear (due to the action of hard reinforcements) become possible. To overcome this problem, many researchers have used dispersed solid lubricant microparticles, such as graphite, in Al-Si alloy matrices. This research analyses the friction and wear properties of A356 Al-Si alloy reinforced with SiC microparticles (40 μm) and graphite macroparticles (200 – 800 μm) in boundary lubricated conditions. The testing has been assessed using two tribometers with different configurations, i.e. ball-on-disc and block-on-disc tribometer. On the ball-on-disc tribometer, a ball made of 100Cr6 steel was sliding on a composite disc under a load of 5 N and a speed of 0.15 m/s for 500 m. On the block-on-disc tribometer, a disc made of 42CrMo4 steel was sliding on a composite block under loads of 50, 100 and 150 N and a speed of 0.5 m/s for 1000 m. In both experiments, the lubricant was engine oil SAE 15W-40. Macro- and microhardness measurements and basic analysis of the wear tracks were also performed. The results showed the beneficial influence of graphite macroparticles addition on tribological properties in boundary lubricated conditions.*
Key words: *A356, hybrid composites, graphite, lubrication, friction, wear.*

1. INTRODUCTION

The A356 alloy is one of the most commonly used Al-Si alloys in metal matrix composite (MMC) fabrication for application in the automotive industry [1-4]. It is a casting alloy consisting of aluminium, silicon and magnesium. Since the silicon content is below 12 wt. % it is classified as a hypoeutectic alloy. This alloy is characterised by its good mechanical characteristics and high corrosion resistance. Its mechanical properties can be significantly improved by appropriate heat treatment, such as the T6 regime [5], or by adding different reinforcements, such as SiC, Al_2O_3, TiO_2, ZrO_2, etc. [6-10]. Reinforcements are mainly in the particulate form since they cost less than fibres and provide more isotropic properties of the composites [11].

In addition to hard reinforcing particles, very often solid lubricant particles, such as graphite, have been used to improve the tribological properties of MMCs [12,13] and to diminish the probability of seizure (intensive adhesive wear) [14,15]. However, there are difficulties since the bonding between the liquid alloys and graphite micro-size particles is problematic, as well as because the graphite microparticles tend to form agglomerates, which can result in a non-homogeneous distribution of particles in the composite matrix and poor overall properties [16,17]. To overcome these disadvantages, graphite macroparticles can be used instead of microparticles [18,19].

There are a huge number of papers that deal with the tribology of MMCs with an A356 alloy base, but most of them investigate only wear in dry sliding conditions. Very few of them are performed in lubricated conditions and deal with both, friction and wear. This paper aims to fill the gap in research and present the results of the composites reinforced with SiC microparticles (40 μm) and graphite macroparticles (200 – 800 μm) tested at two different contact geometries under lubricated sliding conditions at different loads and speeds.

2. EXPERIMENTAL PROCEDURE

The materials for this study were fabricated at the "Vinča" Institute of Nuclear Sciences by semi-solid processing (thixocasting/compocasting). The present research is a sequel to the previously published research on the tribological properties of these materials in dry sliding conditions [19], so the tested materials preparation procedure was the same. The matrix material was a hypoeutectic Al-Si alloy A356 (AlSi7Mg0.3), with the addition of 0.03 wt. % strontium. The role of strontium was to modify the eutectic silicon particles. This material (A356 thixo), obtained through thixocasting, served as a reference material. The average diameter of the used silicon carbide (SiC) microparticles was 40 µm, while the size of graphite (Gr) macroparticles was from 200 to 800 µm. During the compocasting process, the modified matrix was reinforced with 10 wt. % SiC (composite A356-10SiC) or with 10 wt. % SiC and 1 wt. % Gr (hybrid composite A356-10SiC-1Gr). All specimens were subjected to modified T6 heat treatment with the following parameters: solution heat treating at 540 °C for 4 h with water quenching, and artificial ageing at 160 °C for 5 h with water quenching.

Hardness was measured on both, macro- and micro-scale. Macrohardness was measured to diminish the influence of different hardnesses of phases, while microhardness was used to reduce the influence of porosity and other defects. Macrohardness measurements were performed with a load of 5 kgf (HV 5), while the microhardness measurements were performed with a load of 500 gf (HV 0.5). Both measurements were carried out on the same samples, using a Vickers pyramidal diamond indenter and a dwell time of 15 s. For each material, measurements of both hardnesses were repeated at least five times, and an average value with a standard deviation was calculated to obtain the repeatability of the results.

Tribological tests were performed with the same samples in two groups of experiments, i.e. on a ball-on-disc (point contact) and a block-on-disc (line contact) tribometer. On the ball-on-disc tribometer, a ball with a diameter of 6 mm, made of 100Cr6 steel was sliding on a composite disc with an average roughness (*Ra*) of 0.28 µm, under a load of 5 N and a speed of 0.15 m/s for 500 m. On the block-on-disc tribometer, a disc with a diameter of 55 mm and an average roughness (*Ra*) of 0.55 µm, made of 42CrMo4 steel was sliding on a composite block (line contact length of 6 mm) with an average roughness (*Ra*) of 0.35 µm, under the loads of 50, 100 and 150 N and a speed of 0.5 m/s for 1000 m. In both experiments, the lubricant was engine oil SAE 15W-40. Different configurations were used in order to simulate the wide working conditions in the cylinders of gasoline internal combustion engines, compressors and other piston machines. Table 1 shows the calculated values [20] of the initial Hertzian contact stress parameters. Calculations were done for standard A356 alloy (Poisson's ratio 0.33 and modulus of elasticity 72.4 GPa) and specified counter-body steels (Poisson's ratio 0.30 and modulus of elasticity 210 GPa).

Table 1

Initial Hertzian contact stress parameters in used test configurations.

Parameter	Tribometer configuration			
	Ball-on-disc	Block-on-disc		
Normal load, N	5	50	100	150
Maximum Hertzian contact pressure, MPa	729.5	76.1	107.7	131.9
Maximum shear stress in test sample, MPa	221.2	22.9	32.3	39.6
Depth of max shear stress, mm	0.028	0.055	0.077	0.095
Circular contact area diameter, mm	0.114	–	–	–
Rectangular contact area width, mm	–	0.139	0.197	0.241

In ball-on-disc experiments, the coefficient of friction and ball penetration depth were measured continuously during the test. This penetration depth was used as the depth of the wear scar on discs to compute their wear volume after each test. For each sample, three replicate tests were performed to get the average values. Worn surfaces of discs were analysed after testing with a confocal microscope (CM). In block-on-disc experiments, the width of the wear tracks on blocks was measured after each test to compute the volume loss, while the coefficient of friction was tracked continuously during the test. The worn surfaces of blocks were analysed after testing with an optical microscope (OM).

3. RESULTS

3.1 Hardness

Macrohardness and microhardness values of the A356 thixo alloy and the composites A356-10SiC and A356-10SiC-1Gr are shown in Table 2. The repeatability of the results was good, especially for macrohardness values where the deviations were below 5 %. For microhardness, deviations were higher but below an acceptable 10 %. The macrohardness values are practically the same as the previously obtained values for different samples of the same material [18], while the microhardness values are very close to the previously obtained values for the same materials [19]. The A356 thixo alloy showed a macrohardness value that corresponds to the typical hardness value of the sand-casted and T6 heat-treated A356 alloy of 70 HB [21]. The addition of SiC particles (composite A356-10SiC) slightly increased the macrohardness, while the addition of SiC and Gr particles (hybrid composite A356-10SiC-1Gr) increased it further.

Table 2

Hardness of thixocasted A356 alloy and composites.

Material	A356 thixo	A356-10SiC	A356-10SiC-1Gr
Macrohardness HV 5	69.1 (*SD* = 3.2)	73.3 (*SD* = 3.3)	78.1 (*SD* = 3.8)
Microhardness HV 0.5	85.4 (*SD* = 5.7)	90.6 (*SD* = 6.7)	93.0 (*SD* = 9.2)

SD – standard deviation

The microhardness values were higher than the macrohardness values since a lower load was applied; the effect which is confirmed in some previous studies [22,23]. Nevertheless, they correspond to the macrohardness values and follow the same trend, i.e. addition of SiC particles increased the microhardness and the addition of SiC and Gr particles increased it further. It is known that the hardness of the MMCs depends not only on the hardness and other properties of the matrix and secondary phase (reinforcement) but also on the nature of their interface [11]. After the incorporation of SiC and especially Gr particles in the matrix alloy, a complex structure is formed, which affects the hardness of the composites. This could be associated with many phenomena, such as matrix strengthening due to different mechanisms, a decrease in porosity and the effects of reinforcement particle clusters. This complex structure affects hardness and other mechanical properties on all, macro-, micro- and nano-scale [24].

3.2 Friction

The coefficient of friction values are calculated for the steady-state period in both groups of friction experiments, and the average values are shown in Figure 1. This steady-state period for all materials was established after approximately 5 minutes, after a run-in period and intensive change of initial roughness and contact geometry. The values of the coefficient of friction were from 0.08 to 0.09, which suggests that the sliding was performed under the boundary lubrication regime since the approximate values for boundary lubrication are from 0.05 to 0.15 [25]. The obtained values of the coefficient of friction were in accordance with some previous research conducted with similar materials, obtained through the same production process, and with similar or different contact geometry [4,26-28].

The addition of SiC particles slightly increased the coefficient of friction values. This could be attributed to the fact that SIC particles are harder and can protrude and stay in direct contact with the counter-body during testing. This phenomenon was noticed in dry sliding [19,29], as well as in lubricated sliding conditions [4,26]. Interestingly, the addition of graphite did not decrease the coefficient of friction of the hybrid composite. This is mainly due to the fact that the amount of graphite was small. This amount of graphite also did not have an effect in dry sliding conditions [19]. On the other hand, this is in accordance with the higher hardness of hybrid composite since the influence of hardness increases as the system shifts from full-fluid film to boundary lubrication. The results of the block-on-discs experiment (Fig. 1b) also show that the coefficient of friction values slightly increase with the increase of normal load, which is in accordance with the Stribeck curve and boundary lubrication.

3.3 Wear

Wear rate values are calculated for the whole testing period, i.e. as total wear rates in both groups of wear experiments, and the average values are shown in Figure 2.

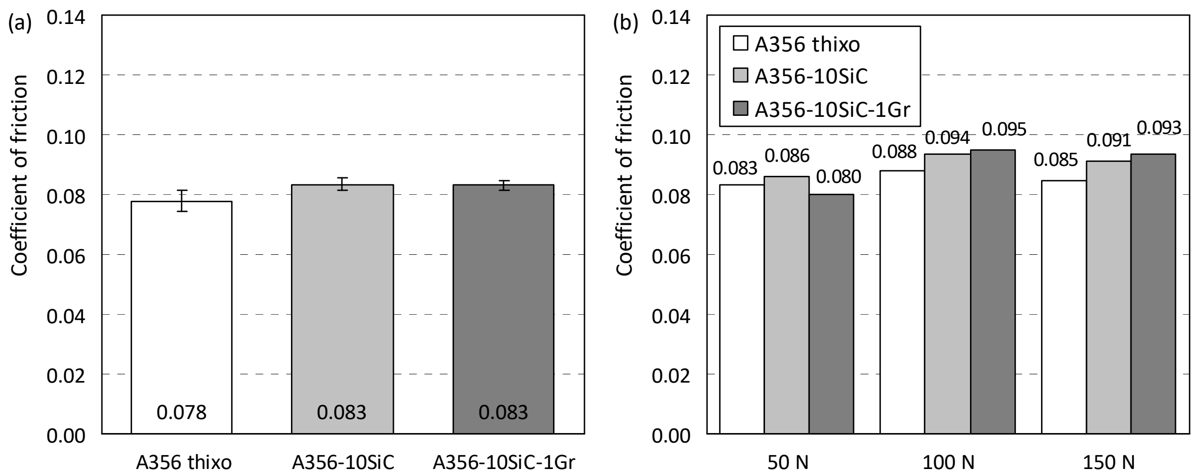

Fig. 1. Coefficient of friction values of thixocasted A356 alloy and composites: (a) ball-on-disc experiment and (b) block-on-disc experiment.

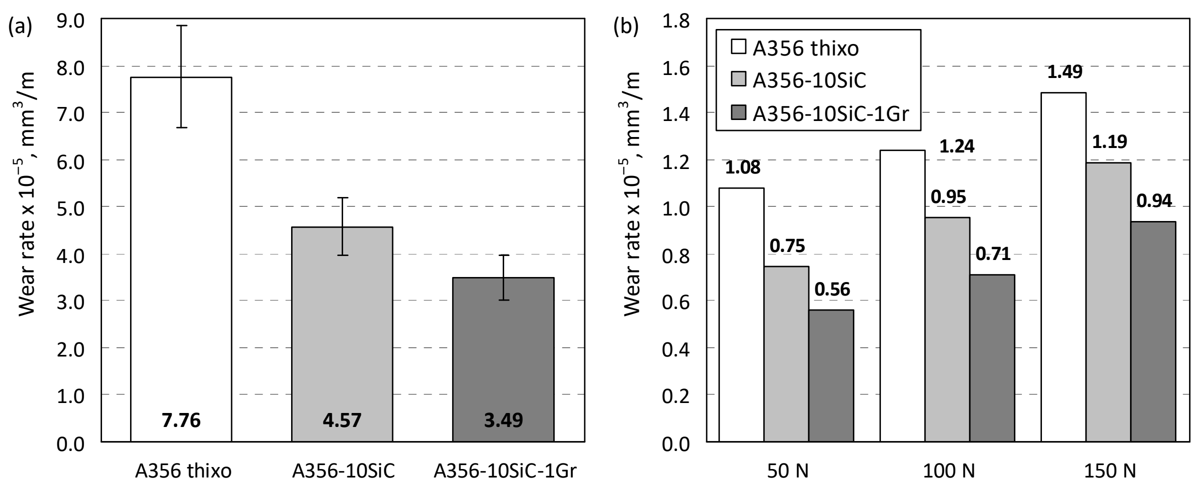

Fig. 2. Wear rate values of thixocasted A356 alloy and composites: (a) ball-on-disc experiment and (b) block-on-disc experiment.

Wear rates of tested materials were in direct correlation with hardness values (Table 2), i.e. softer materials show lower wear resistance. This is obvious if we compare the wear tracks of the tested materials obtained in the ball-on-disc experiment (Fig. 3), i.e. the wear track on the thixocasted A356 alloy (Fig. 3a) is noticeably wider and deeper than the wear track on the hybrid composite A356-10SiC-1Gr (Fig. 3b). Figure 3 also shows that the surfaces were uniformly worn and that there are no visible deep wear pits on the worn surfaces. The presence of graphite particles also could not be noticed on the surfaces.

Between the two configurations, the block-on-disc configuration with the line contact of test samples and counter-body simulates better the working conditions in automotive pistons and cylinder blocks, elements that are made of the tested materials. Babić et al. [30] tested standard A356 alloy and hybrid composite with 10 wt. % SiC (39 μm) and 1 wt. % Gr (35 μm) in lubricated sliding conditions (hydraulic oil ISO VG 46) on a block-on-disc tribometer. Tests were at various conditions of sliding speed (0.25, 0.5 and 1 m/s) and normal load (40, 80 and 120 N). Wear rates of standard A356 alloy were 0.8×10^{-5}, 1.2×10^{-5} and 2.5×10^{-5} mm^3/m at a sliding speed of 0.5 m/s and a normal load of 40, 80 and 120 N, respectively. This is in correlation and very similar to the values obtained in a block-on-disc experiment (Fig. 2b). The obtained values of the wear rates could be used for the calculation of wear factor (specific wear rate) values by dividing them with the applied normal load. The calculated ratios order of magnitude was 10^{-7} mm^3/Nm, which corresponds to the literature data for metallic materials in sliding under boundary lubrication conditions (the interval in this case is from 10^{-9} to 10^{-6} mm^3/Nm) [31].

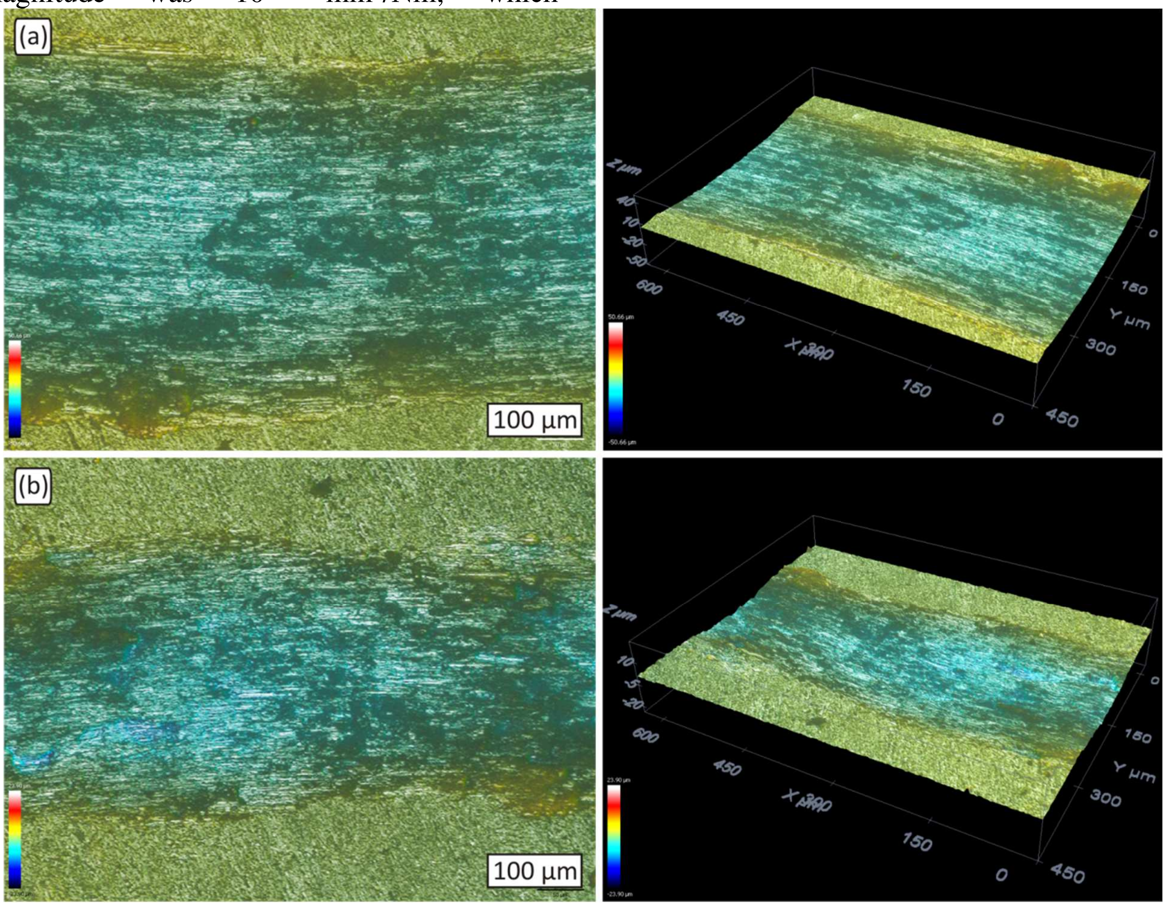

Fig. 3. Wear tracks in 2D and 3D view (CM) after a ball-on-disc experiment: (a) thixocasted A356 alloy and (b) hybrid composite A356-10SiC-1Gr.

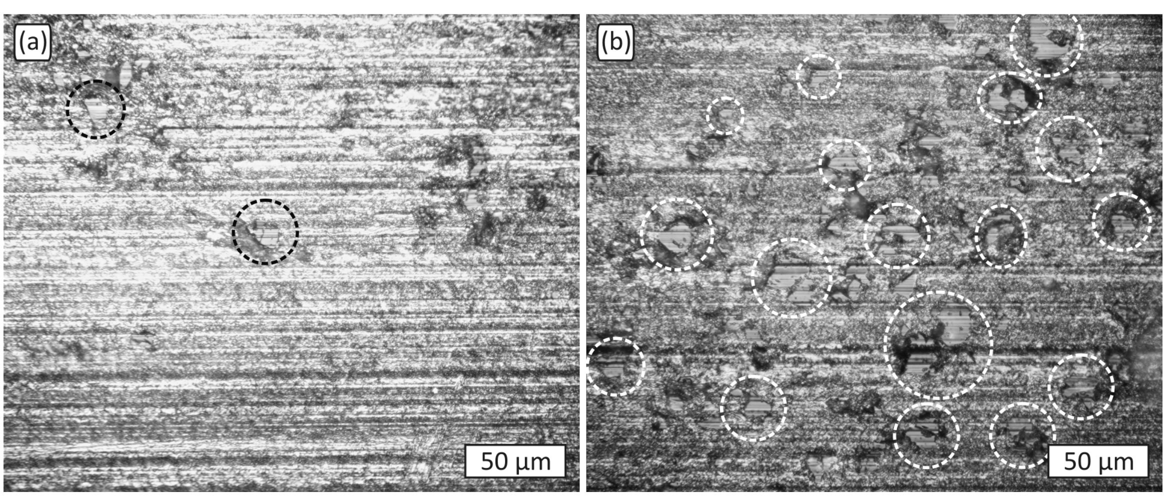

Fig. 4. Worn surface appearance (OM) after a block-on-disc experiment at 150 N: (a) thixocasted A356 alloy and (b) hybrid composite A356-10SiC-1Gr; transferred counter-body material is denoted with circles.

The values of the wear rate in the block-on-disc experiment were lower than the values obtained in the ball-on-disc experiment. This is because the initial Hertzian contact pressure was higher in the case of the ball-on-disc experiment (Table 1) and due to the difference in wear volume measurements between the two experiments. Nevertheless, results are in correlation and the same trend could be noticed. The addition of SiC particles decreased the wear rate by approximately 33 % and the addition of graphite reduced the wear rate further. In the case of the hybrid composite (A356-10SiC-1Gr), the wear rate was reduced by approximately 31 % compared to the composite A356-10SiC and approximately 75 % compared to the thixocasted A356 alloy. Babić et al. [30] got an even bigger reduction and their hybrid composite showed a wear rate that was approximately four times lower than the standard A356 alloy. The existence of this phenomenon in dry sliding conditions was mainly attributed to the formation of a mixed layer of graphite, aluminium and counter-body material on the contact surfaces [19,29]. However, graphite particles could not be noticed on the wear tracks (Fig. 4) of the tested materials. In addition, the coefficient of friction increased in this case, so the presence of a lubricating film that contains graphite could not be expected. The only thing that could induce lower wear of hybrid composite is its higher hardness (both, macro- and microhardness), but this phenomenon should be investigated further and in more detail. On the other hand, transfer of the counter-body (steel disc) material was noticed on the surface of composites with SiC particles (A356-10SiC and A356-10SiC-1Gr). It was noticed even in the case of the thixocasted A356 alloy (Fig. 4a), but was very poor and rare. The most intensive transfer of the counter-body material was in the case of hybrid composite A356-10SiC-1Gr (Fig. 4b). Figure 4 also shows that the worn surface of thixocasted A356 alloy has more frequent and deeper abrasive grooves.

4. CONCLUSION

Friction and wear properties of the A356 Al-Si alloy reinforced with SiC microparticles (40 μm) and graphite macroparticles (200 – 800 μm) were examined in experiments assessed on two different sliding configurations, i.e. on a ball-on-disc and a block-on-disc tribometer. These composites already showed improved tribological properties over the thixocasted A356 alloy in dry sliding conditions, so the idea was to evaluate these properties also in lubricated conditions and to expand their possible area of usage.

The obtained friction and wear results were in correlation with the literature data. The steady-state coefficient of friction values in both groups of experiments ranged from 0.08 to 0.09, which indicates boundary lubricated conditions. Wear values also indicated that the experiments were performed under boundary lubricated conditions. The wear rate values in the ball-on-disc experiment were in the interval from 3.5×10^{-5} to 7.8×10^{-5} mm^3/mm, while in the block-on-disc experiment, they were slightly lower and were in the interval from 0.6×10^{-5} to 1.5×10^{-5} mm^3/mm. This difference was mainly due to the higher initial Hertzian contact pressure with ball-on-disc contact geometry as well as the difference in the wear measurement method.

Results obtained in two different groups of friction and wear experiments were in correlation with each other and with hardness (both, macro- and micro-scale) values, i.e. the same trend regarding coefficient of friction and wear rate values was noticed. The addition of SiC particles slightly increased the coefficient of friction values. It also decreased the wear rate values in the block-on-disc experiment by approximately 33 %, while in the ball-on-disc experiment, this decrease was even bigger. The addition of graphite additionally reduced the wear rate in both groups of experiments by approximately 31 %. This reduction could be attributed to the higher hardness of this composite and the more intensive transfer of the counter-body material in this case, but this phenomenon should be investigated further and in more detail.

5. ACKNOWLEDGEMENT

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Der Einfluss von Graphit-Makropartikeln auf die Reibung und den Verschleiß von A356/SiC/Gr-Verbundwerkstoffen unter Geschmierten Bedingungen

Die Metallmatrix-Verbundwerkstoffe (MMCs) mit Al-Si-Legierungsbasis und Keramikverstärkungen werden häufig in tribologischen Systemen eingesetzt, z. B. in Automobilkolben, Zylinderblöcken, Gleitlagern und in anderen Systemen, wo Grenzschmierung auftreten kann. Unter diesen Bedingungen sind intensiver, adhäsiver Verschleiß (aufgrund des Festfressens der Al-Si-Legierung) und abrasiver Verschleiß (aufgrund der harten Verstärkungswirkung) möglich. Um dieses Problem zu lösen, haben viele Forscher die Festschmierstoff-Mikropartikel wie Graphit den Al-Si-Legierungsmatrizen hinzugefügt. Dieser Artikel analysiert die Reibungs- und Verschleißeigenschaften der A356 Al-Si-Legierung, die unter Bedingungen der Grenzschmierung mit SiC-Mikropartikeln (40 µm) und Graphit-Makropartikeln (200 – 800 µm) verstärkt wurde. Die Tests wurden mit zwei Tribometern mit unterschiedlichen Konfigurationen bewertet, d. h. mit einem Kugel-auf-Scheibe-Tribometer und einem Stift-auf-Scheibe-Tribometer. Beim Kugel-auf-Scheibe-Tribometer gleitet eine Kugel aus 100Cr6-Stahl unter einer Belastung von 5 N und einer Geschwindigkeit von 0,15 m/s 500 m lang auf einer Scheibe aus Verbundwerkstoff. Beim Stift-auf-Scheibe-Tribometer gleitet ein Stift aus 42CrMo4-Stahl auf einem Block aus Verbundwerkstoff unter Belastung von 50, 100 und 150 N und einer Geschwindigkeit von 0,5 m/s über 1000 m. In beiden Versuchen war das Schmiermittel das Motoröl SAE 15W-40. Darüber hinaus wurden Makro- und Mikrohärtemessungen sowie eine grundlegende Analyse der Verschleißspuren durchgeführt. Die Ergebnisse zeigten den positiven Einfluss der Zugabe von Graphit-Makropartikeln auf die tribologischen Eigenschaften unter Bedingungen der Grenzschmierung.

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