Wear Behavior of Hypereutectic Al-18Si Composites Under Linear Reciprocating Sliding

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Abstract. Aluminum and its alloys are widely used due to their good characteristics like low density, non-ferromagnetism, resistance to corrosion, high electrical and thermal conductivity, non-flammability, non-toxicity, and others. Hypereutectic Al-Si alloys are finding their application for pistons, due to their good thermal conductivity, high strength-to-weight ratio and good corrosion resistance. Since pistons are operating under high loads there is a need for improvement of their mechanical and tribological characteristics. Mechanical and tribological characteristics and microstructure of composites depend on the fabrication methods and size of reinforcement particles. The investigation of mechanical and tribological properties of hypereutectic Al-18Si based composites was done on composites particulate reinforced with 0.5 wt.% Al_2O_3 (approx. Size 20–30 nm), 10 wt.% SiC (approx. Size 30 μm) and 1 wt.% Gr (approx. Size 17 μm). Tribological tests were done on apparatus with reciprocating linear motion in lubricated sliding conditions, at a sliding speed of 0.5 m/s, sliding distance of 1000 m and normal loads of 100, 200 and 300 N. Hardness of composites decreased with the addition of reinforcements and intermetallic phases and large primary Si particles were present in the microstructure. The increase in normal load increased wear while the coefficient of friction decreased with the increase in normal load. This study shows the potential of hypereutectic Al-18Si based composites reinforced with nano Al_2O_3, and micro SiC and Gr particles to be used for highly loaded pistons since the composites showed improved mechanical and tribological properties over the base alloy.

Keywords: hypereutectic Al-Si · wear · Al-Si composites · reciprocating sliding

1 Introduction

In recent years, there has been a growing interest in the development and utilization of advanced materials with enhanced properties to meet the demands of various engineering solutions. Aluminum alloys and composites based on these alloys are interesting due to their low density, high electrical and thermal conductivity, good specific strength,

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good recycling possibilities [1], good thermal conductivity [2], high corrosion resistance [3] and favorable casting and weldability properties [4–6]. Al alloys have wide applications in the automotive industry for engine blocks, pistons, brakes, engine liners, and others [7, 8]. There are three types of Al alloys: hypoeutectic (Si content less than 12.6 wt.%), eutectic (Si content around 13 wt.%) and hypereutectic alloys (Si content higher than 13 wt.%) [9]. Hypereutectic Al-Si alloys have a low coefficient of thermal expansion, excellent casting characteristics, good weldability, high wear resistance, and high-temperature strength [10, 11]. In order to improve some properties of Al alloys, composites are formed. Al matrix composites and nanocomposites are used in various fields of industry [12–15]. The source of Al base material is often provided via a recycling route [16]. Ceramics such as SiC, Al_2O_3, TiC, B_4C and others, and Gr as a solid lubricant [13, 17–19] are mainly used as reinforcements. The most applied fabrication methods for the production of hypereutectic alloys and composites are conventional casting, gravity casting and stir casting, but recently there has been more and more investigation of thixo and rheocasted hypereutectic alloys and composites [4]. Baby et al. [20] investigated rapidly solidified and T6 heat-treated Al alloy with 25 wt.% Si. The tribological tests were done in dry sliding conditions on a tribometer with pin-on-disc contact geometry and on a linear reciprocating tribometer, for different normal loads (40–120 N) at a constant time of 30 min. For the tribometer with pin-on-disc contact geometry sliding speed was from 0.8 to 1.5 m/s while for the linear reciprocating tribometer sliding speed was from 0.2 to 0.45 m/s. For pin-on-disc tribometer, coefficient of friction (CoF) was in the interval 0.35–0.49 and wear was in the interval 10–35 mg, while for linear reciprocating motion, CoF was from 0.39 to 0.47 and wear was from 1 to 6 mg. Malleswararao et al. performed dry and lubricated reciprocating tribological tests on hypereutectic Al allow with 17 wt.% Si at room temperature [21]. The Al-Si alloy was fabricated by rheo-stir squeeze casting procedure and heat treated with the T6 regime. Engine oil SAE15W40 was used as a lubricant, while some specimens were coated with CrN + a-C:H (metal-free amorphous carbon). Experiments were done for ball-on-plate contact geometry, sliding distance of 50 m, normal load of 5–30 N at a frequency of 20 Hz, with a 2 mm stroke length. For dry and lubricated sliding conditions CoF decreased with an increase in normal load and was in interval from 0.78 to 0.41 and from 0.094 to 0.064, respectively. Specific wear rate in all testing conditions increased with an increase in normal load from 5 to 20 N after which decreased with an increase in normal load, and for dry sliding conditions, the highest specific wear rate was 2.9×10^{-3} mm^3/Nm and in lubricated sliding 4.0×10^{-4} mm^3/Nm. Mohamadigangaraj et al. [22] investigated composites based on hypereutectic A390 Al-Si alloy reinforced with 10 wt.% SiC (average particle size was 45 μm). Composites were produced by compocasting method with different stirring speeds (450, 550 and 650 rpm), stirring times (10, 15 and 20 min) and stirring temperatures (610, 620 and 630 °C). The microstructure, hardness and tribological properties were investigated. The microstructure of specimens showed that with a decrease in stirring temperature uniformity of SiC particle distribution increases, and with an increase in temperature the SiC agglomeration, as well as accumulation of primary Si particles around SiC particles, increases. Tribological tests were done in dry sliding conditions, on a tribometer with pin-on-disc contact geometry under a normal load of 10 N, at a sliding distance of 1000 m and sliding speed of 0.5 m/s.

When compared to the as-casted and stirred matrix material, the composite Al18Si + 10 wt.% SiC had the lowest CoF and wear rate. Carvalho et al. [17] investigated the dry reciprocating sliding behavior of Al alloy with 11Si reinforced with 2 wt.% CNT and 5 wt.% SiC (hybrid composite). Tribological tests were done at pin-on-plate contact geometry, normal load of 10 N, amplitude of 10 mm, sliding distance of 148 m, sliding speed of 0.02 m/s, and duration of 2 h. Hardness measurements showed that compared to the base alloy hardness increases with reinforcement addition. Wear decreased with the addition of 2 wt.% CNT, 5 wt.% SiC and 2 wt.% CNT + 5 wt.% SiC for 8%, 6% and 22%, respectively, when compared to the base alloy. CoF was in the interval 0.62–0.65.

This study aims to determine the tribological characteristics of hypereutectic Al-Si composites reinforced with 0.5 wt.% of Al_2O_3, 10 wt.% SiC and 1 wt.% Gr, in lubricated sliding conditions on a tribometer with linear reciprocation motion. Through comprehensive experimental analyses, the influences of these reinforcements on friction, wear, and mechanical properties of the composite materials are determined.

2 Materials and Methods

2.1 Materials

Two hybrid composite materials (C1 and C2) were selected for investigation and their characteristics were compared to the base material (BM). The base material was Al18Si alloy modified with strontium (Sr). Nanoparticles of Al_2O_3 (20–30 nm), and microparticles of SiC (30 µm) and Gr (17 µm) were selected as reinforcements. The designations of materials and the content of reinforcement are shown in Table 1. Materials were produced by thixo/compocasting method at the Institute of Nuclear Sciences "Vinca".

Table 1. Material designation and reinforcement content.

Material designation	Base material	Reinforcement wt.%
BM-base material	**Al18Si**	**-**
C1	**Al18Si**	**$10SiC + 0.5Al_2O_3$**
C2	**Al18Si**	**$10SiC + 0.5Al_2O_3 + 1Gr$**

2.2 Experimental Procedures

Vickers hardness tests were done on a WPM Leipzig hardness tester at the University of Kragujevac, Faculty of Engineering. The load on the indentation pyramid was 98.1 N. Tribological tests were done on tribometer with linear reciprocating sliding motion and conformal contact [23]. The maximum stroke of the tribometer is 600 mm, while in this case stroke was 450 mm. The sample materials were machined into blocks with dimensions 16 × 12 × 6 mm, where the surface in contact was 16 × 6 mm. Counterbody was a plate made of 42CrMo4 steel with dimensions 600 × 300 mm. Tests were done in lubricated sliding conditions with engine oil SAE 5W-30, and characteristics of the lubrication oil can be found elsewhere [24]. Normal load was 100, 200 and 300 N, sliding speed was 0.5 m/s and sliding distance was approximately 1000 m. Wear was measured on precision balance Radwag PS 1000.R2, while CoF was monitored in real-time during experiments.

3 Results and Discussion

3.1 Microstructure

Analysis of the microstructure was done on a scanning electron microscope (SEM) at the University of Belgrade, Faculty of Mining and Geology. The microstructure of BM and composite C2 are shown in Fig. 1.

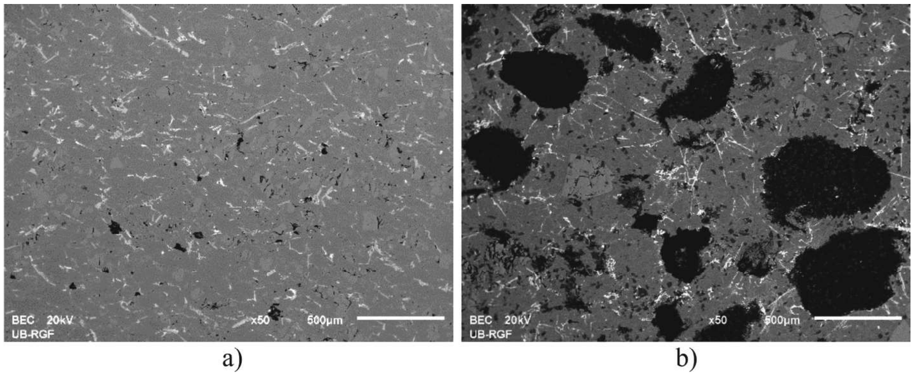

Fig. 1. Microstructure of the tested materials a) BM and b) composite C2.

From Fig. 1 it can be noticed that there are a lot of intermetallic phases present in both materials. In BM material there are primary Si particles of smaller size (Fig. 1 a), while in composite C2 their size increased (Fig. 1 b), and there are agglomerates of reinforcement particles present as well. The agglomeration of reinforcement particles is probably due to their low wetting [25, 26]. The intermetallic phases were Mg_2Si, Al-Fe-Si, Al-Ni-Cu-(Fe) and Al-Cu-Mg-Si, intermetallic phases are, usually, brittle so their presence in the material is unfavorable. Phase MgSi is most likely the Mg_2Si phase, as observed in other studies [27, 28]. Mg_2Si phase has a lower density (1.88 g/cm^3), higher elasticity modulus, and approximately the same microhardness compared to Si. This phase is often a reinforcing phase in Al-based composites [27]. Alongside with this phase, there is also the Al-Fe-Si phase, in the form of needles or elongated plates. It is presumed that this phase is β-Al_5FeSi, as its shape corresponds to the phase present in studies [29, 30]. The β-Al_5FeSi phase has an unfavorable effect on the material by being the cause of stress formation. The intermetallic phase Al-Ni-Cu-(Fe), mainly appearing in the form of Chinese characters or irregular shapes, is one of the brightest phases present in Fig. 1. According to Cáceres et al. [31], Cu-rich phases contribute to increased porosity when the Cu content exceeds 0.2 wt.%; pores form due to a combination of higher hydrogen gas pressure, heavier feeding, and increased liquid metal rich in Cu shrinkage. The irregularly shaped intermetallic phase Al-Cu-Mg-Si, according to other studies [30, 32, 33], is the $Al_5Cu_2Mg_8Si_6$ phase.

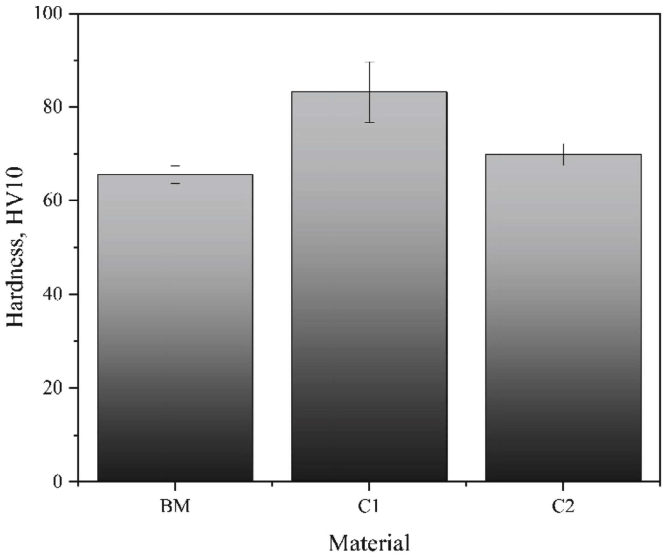

Fig. 2. Hardness of the materials.

From Fig. 2 it can be noticed that with the addition of 10 wt.% SiC microparticles and 0.5 wt.% Al_2O_3 nanoparticles the hardness increases (composite C1). The addition of 1 wt.% of Gr microparticles to composite C1 (composite C2) induced hardness decreases, but it is still harder than the base material. Stojanovic et al. had a similar conclusion, where the composite A356 + 10SiC had a higher hardness than composite A356 + 10SiC + 1Gr [34]. Shanmughasundaram and Subramanian [35] also showed that with the addition of Gr particles in eutectic Al-Si alloy hardness decreases.

In Fig. 3 it can be noticed that with an increase in normal load, wear is increasing for all materials. The lowest wear was for composite C1 (Al18Si + 10SiC + $0.5Al_2O_3$) while the highest was for composite C1 which shows that the addition of 1 wt.% of Gr did not influence wear. For CoF (Fig. 4) it can be noticed that with an increase in normal load, the CoF decreases for all tested materials. Similar behavior has been noticed in dry sliding tribological tests of other authors [21, 36, 37]. The results for CoF indicate that the lubrication method was not adequate since the values correspond to the CoF in dry sliding lubricating conditions.

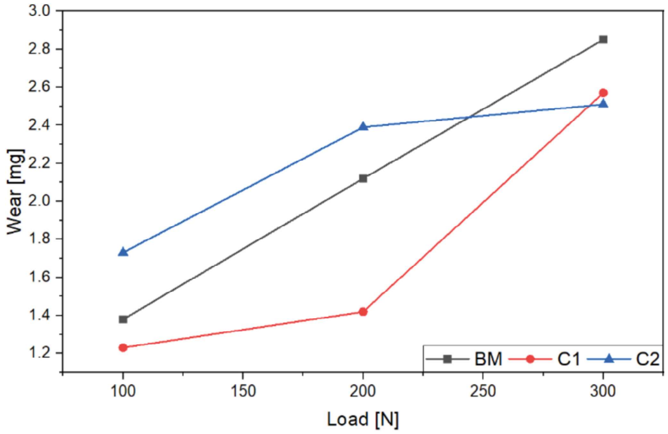

Fig. 3. Results of tribological testing-Wear of the materials.

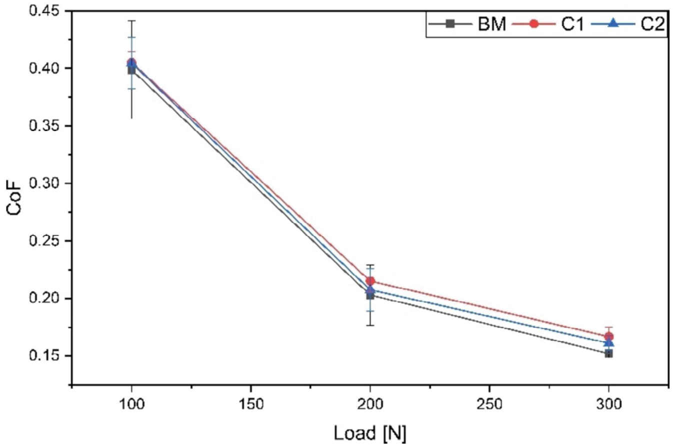

Fig. 4. Results of tribological testing-Coefficient of friction of the materials.

4 Conclusion

The presented study is focused on the characterization of the developed hybrid composites with Al18Si base alloy and Al_2O_3 nanoreinforcement, and SiC and Gr microreinforcement via the thixo/compocasting process. Microstructure, hardness, wear rate and CoF were analysed. The thixocasting fabrication process gave good distribution and coarse primary Si particles of smaller size. With the addition of SiC, Al_2O_3 and Gr the agglomeration of SiC and Al_2O_3 particles could be noticed, as well as an increase in the size of primary Si particles. With the addition of SiC and Al_2O_3 (composite C1) hardness increased when compared to the base alloy, while the addition of Gr to composite C1 decreased hardness. Since Al18Si alloys are often used for cylinders, cylinder liners and pistons, the tribological tests were done on a tribometer with linear reciprocal sliding movement. With the increase in normal load, wear increased while CoF decreased for all tested materials. This type of behavior is characteristic for dry sliding tests. The tribological results indicate that there was not enough oil and that this type of lubrication is not adequate for the applied tribometer. This study gives valuable insights into the potential application of hybrid hypereutectic Al-Si based composites. The results give a contribution to future research in terms of optimization of the performance and applicability of hypereutectic Al-Si composites in automotive and industry in general.

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