UDK 66.017:620.168:539.92
Original scientific article/Izvirni znanstveni članek

ISSN 1580-2949
MTAEC9, 46(5)497(2012)

MECHANICAL AND TRIBOLOGICAL CHARACTERISTICS OF STIR-CAST Al-Si10Mg AND SELF-LUBRICATING Al-Si10Mg/MoS_2 COMPOSITES

MEHANSKE IN TRIBOLOŠKE LASTNOSTI Z MEŠANJEM ULITIH KOMPOZITOV Al-Si10Mg IN SAMOMAZALNIH KOMPOZITOV Al-Si10Mg/MoS_2

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Prejem rokopisa – received: 2012-03-20; sprejem za objavo – accepted for publication: 2012-05-24

The mechanical and tribological characteristics of aluminium-molybdenum-disulphide self-lubricating composites have been investigated and compared to the Al-Si10Mg alloy. Al-Si10Mg/4MoS_2 display the finest microstructures due to a higher fraction of MoS_2 added. The densities of Al-Si10Mg/2MoS_2 and Al-Si10Mg/4MoS_2 were marginally higher than in the case of the aluminium alloy by 1 % and 2 % mass fractions, respectively. The ultimate tensile strength decreases considerably due to the additions of 2 % and 4 % MoS_2 by 15 % and 22 %, respectively, compared to the Al-Si10Mg alloy. It was seen that while the Al-Si10Mg alloy shows a predominantly ductile fracture (fibrous regions), the composite specimens (with an MoS_2 addition) show an increase in the mixed mode (ductile and brittle regions). Al-Si10Mg/2MoS_2 and Al-Si10Mg/4MoS_2 show an enormous decrease in the wear rate by 55 % and 65 %, respectively, compared with the Al-Si10Mg alloy. The decrease in the wear occurs due to the presence of an MoS_2 layer, which forms a film on the wear surface.

Keywords: aluminium-molybdenum-disulphide self-lubricating composites

Preiskovane so bile mehanske in tribološke značilnosti aluminij-molibden disulfidnih samomazalnih kompozitov in primerjane z zlitino Al-Si10Mg. Al-Si10Mg/4MoS_2 ima najdrobnejšo mikrostrukturo zaradi večjega deleža dodanega MoS_2. Gostota Al-Si10Mg/2MoS_2 in Al-Si10Mg/4MoS_2 je bila navidezno večja za masni delež 1 % oziroma 2 %. Končna natezna trdnost se je v primerjavi z zlitino Al-Si10Mg občutno zmanjšala za 15 % oziroma 22 % pri dodatku 2 % oziroma 4 % masnega deleža MoS_2. Izkazalo se je, da pri zlitini Al-Si10Mg prevladuje žilav prelom (vlaknata področja), pri kompozitnih vzorcih (z dodatkom MoS_2) pa mešan prelom (duktilna in krhka področja). Al-Si10Mg/2MoS_2 in Al-Si10Mg/4MoS_2 izkazujeta občutno povečanje odpornosti proti obrabi, in sicer 55 % oziroma 65 % v primerjavi z zlitino Al-Si10Mg. Zmanjšanje obrabe je zaradi sloja MoS_2, ki tvori tanko plast na obrabni površini.

Ključne besede: aluminij-molibden disulfidni samomazalni kompoziti

1 INTRODUCTION

Aluminium-silicon alloys and composites are being used in automotive applications like pistons, brake rotors and engine-block cylinder liners[1,2]. Tribological behaviour is an important aspect in the use of aluminium metal-matrix composites in automotive applications. The wear behaviour of Al-Si alloys can be further enhanced by adding ceramic particles. Abrasive particles like silicon carbide, alumina, and diamond are added to improve the tribological behaviour by increasing the hardness of a composite[3–5]. Nevertheless, lubricating particles like graphite and MoS_2 have also been added to improve the tribological behaviour of different materials by providing a solid lubricating layer[6,7]. The additions of these particles considerably affect the mechanical behaviour of the composites.

There are various methods of producing composites like blending and consolidation, vapour deposition and consolidation, stir casting, infiltration process, spray deposition and consolidation, as well as in-situ reacting process[8]. Of all these processes, stir casting is the simplest and the most economical method. Stir-cast self-lubricating composites have been successfully developed by adding graphite particles[9]. It has also been suggested that these composite materials have the capacity to achieve low friction and wear of the contact surfaces without any external supply of lubrication during the sliding. However, graphite films fail in lower loads and shorter lifetimes compared with MoS_2[10]. Self-lubricating Al-MoS_2 composites have been prepared by using the powder-metallurgy route[11]. However, neither the preparation of MoS_2- based composites by stir casting nor the characterisation of Al-Si10Mg/MoS_2 composites have been reported in literature.

In this investigation, two self-lubricating composites of molybdenum disulphide, namely, Al-Si10Mg/2MoS_2 and Al-Si10Mg/4MoS_2 have been produced with the stir-casting route. The changes in the mechanical and tribological properties caused by the addition of MoS_2 are studied and compared with the Al-Si10Mg alloy.

2 MATERIALS AND METHODS

2.1 Preparation of the composite

The Al-Si10Mg aluminium alloy (**Table 1**) with a density of 2640 kg/m^3 was used in this investigation as the matrix material. The Al-Si10Mg alloy has excellent resistance to corrosion in both normal atmospheric and marine environments collectively exhibiting high strength and hardness.

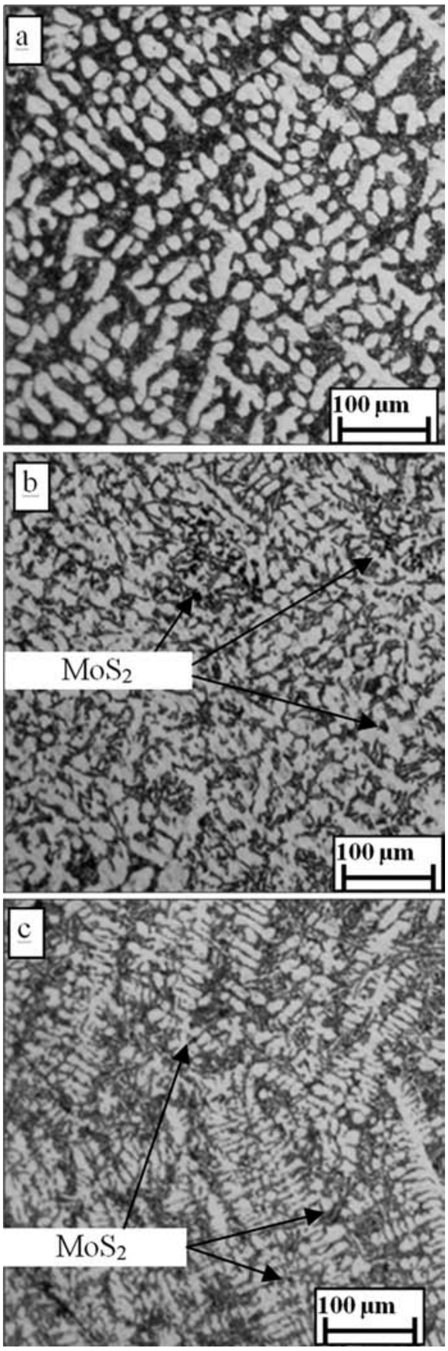

Figure 1: Microstructures of the materials: a) Al-Si10Mg, b) Al-Si10 Mg/2MoS_2, c) Al-Si10Mg/4MoS_2
Slika 1: Mikrostruktura materiala: a) Al-Si10Mg, b) Al-Si10Mg/ 2MoS_2, c) Al-Si10Mg/4MoS_2

Table 1: Chemical composition of the aluminium alloy used (mass fractions, *w*/%)
Tabela 1: Kemijska sestava uporabljene aluminijeve zlitine (mas. deleži, *w*/%)

Mg	Si	Fe	Mn	Others*	Al
0.2 to 0.6	10.0 to 13.0	0.6 max	0.3 to 0.7	1.5 max	balance

* (Cu, Ni, Zn, Pb, Sn and Ti)

The Al-Si10Mg alloy was charged into an electrical resistance-heated furnace modified for this investigation. The melting of the Al-Si10Mg alloy was carried out under argon atmosphere at 1073 K. Molybdenum-disulphide (MoS_2) solid lubricant with an average particle size of 1.5 µm and a density of 4600 kg/mm^3 (**Figure 1**) was used as the reinforcement in this investigation. The MoS_2 particulates were incorporated into the molten metal and stirred continuously for ten minutes. The molten mixture was solidified in a cast-iron die in the form of a cylindrical pin with a diameter of 14 mm and a length of 70 mm.

2.2 Testing of the materials

The density of composites was determined using a top-loading electronic balance (Mettler Toledo make) according to the Archimedean principle. The microstructure of the composite specimens was identified using a Carl Zeiss Goettingen optical microscope. The specimens were metallographically polished to obtain an average roughness value of 0.8 µm. The tensile testing was carried out using a Hounsefield tensometer. The ultimate tensile strength of the specimens was calculated from the load at which a fracture occurred. The morphology of worn surfaces of the composite specimens was examined by using a JEOL T100 Scanning Electron Microscope (SEM). The hardness was measured by using a Zwick hardness tester at a load of 100 g. The dry-sliding wear behaviour of the composites was studied using a pin-on-disc apparatus. The disc material was made of the EN-32 steel with a hardness of 65 HRC. The difference in weights before and after the test was taken as weight loss. The wear rate was calculated on the basis of the difference in the weights of a specimen using the following formula:

$$\text{Wear rate} \qquad [WR] = \frac{W}{9.81 \rho D} \quad \text{mm}^3/\text{km} \qquad (1)$$

where W/kg = mass loss, ρ/(kg/mm^3) = density of the material, D = sliding distance

Table 2: Mechanical properties of the Al-Si10Mg alloy and the composites
Tabela 2: Mehanske lastnosti Al-Si10Mg zlitine in kompozitov

Material	Density kg/m^3	UTS MPa	Hardness HV	Elongation %	Decrease in UTS, %	Increase in hardness, %
Al-Si10Mg	2640	218.45	102	1.66	-	-
Al-Si10Mg/2MoS$_2$	2670	185.31	145	1.22	15	42
Al-Si10Mg/4MoS$_2$	2697	170.28	148	1.10	22	45

3 RESULTS AND DISCUSSION

3.1 Microstructures

Optical micrographs of the Al-Si10Mg alloy and of the composites (**Figures 1a** to **c**) show as-cast (dendritic) structures consisting of silicon particles in a eutectic matrix. The microstructures of the composites (Al-Si10Mg/2MoS$_2$ and Al-Si10Mg/4MoS$_2$) are significantly finer, affected probably by the heterogeneous nucleation caused by MoS$_2$ particles. Al-Si10Mg/4MoS$_2$ exhibits the finest microstructure due to the higher fraction of MoS$_2$ added. Figures 1b and 1c show that MoS$_2$ particles were uniformly distributed in the matrix.

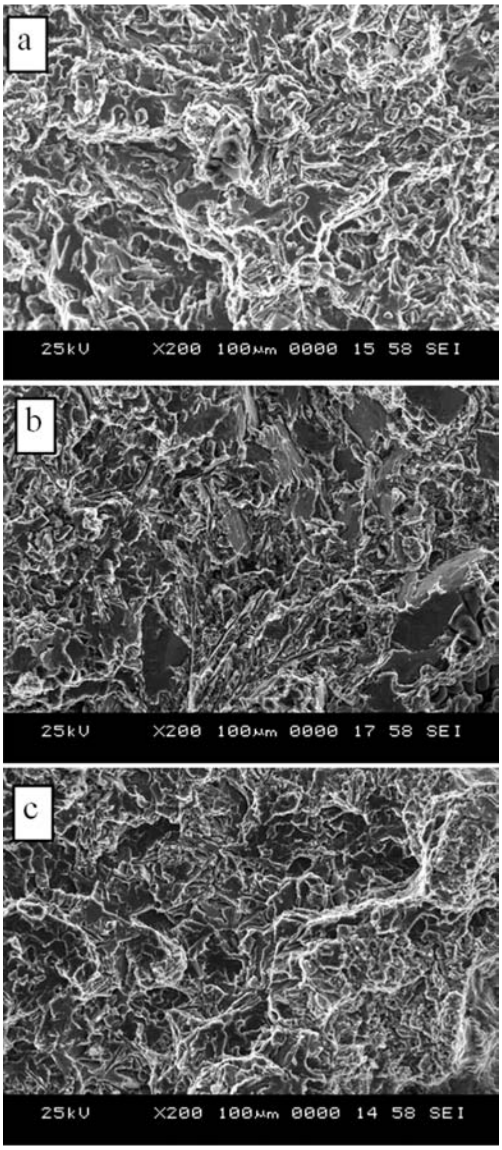

Figure 2: Fracture analysis of the materials: a) Al-Si10Mg, b) Al-Si10Mg/2MoS$_2$, c) Al-Si10Mg/4MoS$_2$
Slika 2: Analiza prelomov materiala: a) Al-Si10Mg, b) Al-Si10Mg/2MoS$_2$, c) Al-Si10Mg/4MoS$_2$

3.2 Mechanical properties

The mechanical properties of the composites (density, hardness, and tensile strength), given in **Table 2**, show the average properties of various test specimens at different positions.

The density of MoS$_2$ is higher than that of the aluminium alloy and hence an increase in the MoS$_2$ content will raise the density of the composite. The densities of Al-Si10Mg/2MoS$_2$ and Al-Si10Mg/4MoS$_2$ were marginally higher than the density of the aluminium alloy by 1 % and 2 %, respectively. A similar increase in the density of the composites was achieved by adding SiC[12] and Al$_2$0$_3$[13] by various authors.

The ultimate tensile strength [UTS] of Al-Si10Mg was approximately 218 MPa. It was reported in previous researches that an addition of alumina to AA6061 and AA7005 causes an increase in the tensile strength[14]. Similar results were reported for SiCp/aluminium-alloy composites[15] and aluminium-alumina, aluminium-illite and aluminium-silicon carbide particle composites[5]. In contrast to this, the studies on an addition of alumina to the 2024 Al alloy have shown a decrease in UTS[16]. Similar results were obtained for an addition of graphite to aluminium[17]. The tensile strength decreases considerably due to the additions of 2 % and 4 % by mass MoS$_2$ by 15 % and 22 %, respectively. The observed decrease in UTS may be due to various mechanisms like the particle pull-out and crack propagation, which are initiated by the presence of MoS$_2$.

The elongation of the composites decreases slightly less than in the case of the Al-Si10Mg alloy indicating that an addition of MoS$_2$ lowers the ductility of a composite. A similar result was observed in the SiC reinforcement of the 2124, 7075 alloys and monolithic aluminium[18,19].

3.3 Fracture surface

Figures 2a to **c** show the SEM fractographs of Al-Si10Mg, Al-Si10Mg/2MoS$_2$ and Al-Si10Mg/4MoS$_2$,

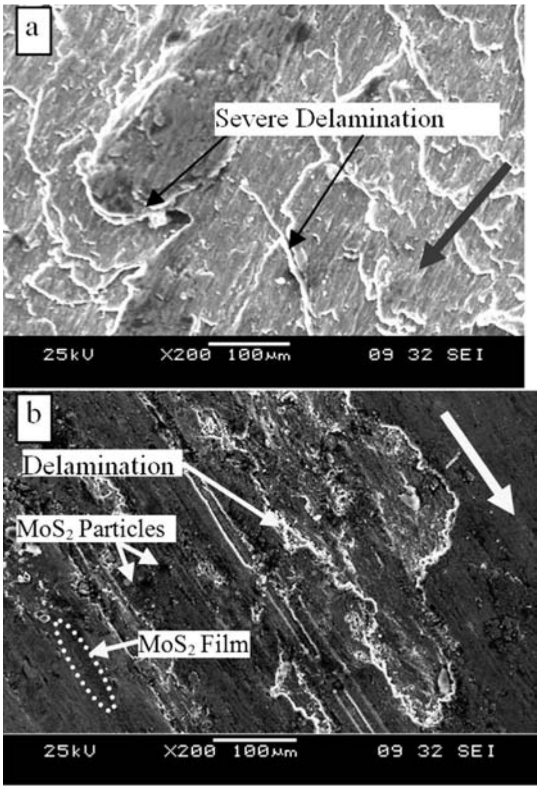

Figure 3: Wear behaviour of the Al-Si10Mg alloy and the composites
Slika 3: Obraba Al-Si10Mg-zlitine in kompozitov

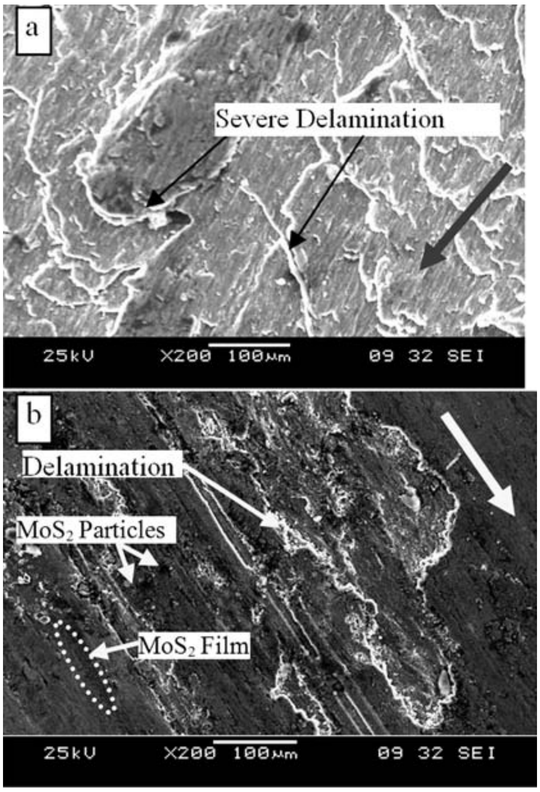

Figure 4: Wear-surface SEM micrographs at a load of 50 N and a speed of 5 m/s of: a) Al-Si10Mg, b) Al-Si10Mg/2MoS$_2$
Slika 4: SEM-posnetek obrabljene površine pri obremenitvi 50 N in hitrosti 5 m/s za: a) zlitine Al-Si10Mg, b) Al-Si10Mg/2MoS$_2$

respectively. From the fractographs of the tensile-test specimens (**Figure 2**) it can be seen that, in the aluminium-matrix alloy, the fracture was primarily transgranular with a microscopic void formation; later the progressive growth and the final coalescence around the reinforcement particles can be observed. It can also be seen that while the Al-Si10Mg alloy shows a predominantly ductile fracture (fibrous regions), the composite specimens show an increase in the mixed mode [ductile and brittle regions]. In addition, the composite samples also show the features like particle pullout, crack growth, and propagation typical of a brittle fracture.

3.4 Wear behaviour

Dry-sliding wear tests were conducted according to ASTM G-99 using a pin on a disc apparatus under an applied load of 50 N for a sliding speed of 5 m/s. The wear rate plotted against the sliding distance is shown in **Figure 3**.

The Al-Si10Mg alloy experiences the maximum wear rate. The wear mechanism was studied using a SEM micrograph of the worn surface of the Al-Si10Mg alloy (**Figure 4a**), revealing severe delamination that is an indication of an adhesive wear. Al-Si10Mg/2MoS$_2$ and Al-Si10Mg/4MoS$_2$ show an enormous decrease in the wear rate by 55 % and 65 %, respectively, compared with the Al-Si10Mg alloy. The decrease in the wear is due to the presence of the MoS$_2$ layer, which forms a film on the wear surface. This in evident in the SEM micrograph of Al-Si10Mg/2MoS$_2$ (**Figure 4b**) where the MoS$_2$ particles form a film in certain regions, partially reducing the ploughing and delamination.

4 CONCLUSION

In this research work, Al-Si10Mg/MoS$_2$ composites were fabricated using the stir-casting technique and the mechanical and tribological characteristics were studied. The following important observations can be noted:

1. UTS, elongation percentage and hardness decrease with an addition of MoS$_2$ particles to Al-Si10Mg. However, the densities of the composites are higher than the density of the Al-Si10Mg alloy.
2. A uniform distribution of MoS$_2$ is observed on the optical micrographs.
3. The improved wear resistance of Al-Si10Mg/MoS$_2$ composites is better than the wear resistance of the Al-Si10Mg alloy.

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