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EXPERIMENTAL ANALYSIS OF THE WEAR BEHAVIOR OF HYBRID METAL-MATRIX COMPOSITES OF LM25Al WITH EQUAL VOLUMES OF SiC + TiO_2

ANALIZA OBRABE HIBRIDNEGA KOMPOZITA S KOVINSKO OSNOVO LM25Al Z ENAKIM VOLUMENSKIM DELEŽEM SiC + TiO_2

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In the present work tribological behavior of aluminium alloy LM25 reinforced with SiC and TiO_2 fabricated with the stir-casting process is investigated. The wear resistance and frictional properties of the hybrid metal-matrix composite were studied by performing a dry-sliding-wear test using a pin-on-disc wear tester. The experiments were conducted at a constant sliding velocity of 1.04 m/s and sliding distance of 628 m with various loads of (3, 4, 5) kg and the particle volume fraction ranging from 5–15 %. The results show that the reinforcement of the metal matrix with SiC and TiO_2 reduces the wear rate at room temperature. The results also indicate that the wear of the test specimens increases with the increasing load and sliding distance. The coefficient of friction decreases with the load and increasing volume content of the reinforcement. The hardness of the hybrid-composite test specimens increases with the increasing volume fraction of the particle reinforcement of SiC and TiO_2. The microstructure analysis reveals that SiC and TiO_2 particulates are uniformly distributed in the matrix. The wear surfaces are examined with a scanning electron microscope which indicates abrasive wear mechanism due to the hard ceramic particles on the worn surface.

Keywords: dry-sliding wear, LM25Al alloy hybrid composite, equal volumes of SiC + TiO_2, wear mechanism

V tem delu je preiskovano tribološko vedenje aluminijeve zlitine LM25, ojačane s SiC in TiO_2, izdelane po postopku vmešavanja v talino. Preizkušena je bila odpornost proti obrabi in lastnosti pri trenju hibridnega kompozita s kovinsko osnovo s suhim trenjem na napravi "pin-on-disc" za preizkušanje obrabe. Preizkusi so bili izvršeni pri konstantni hitrosti drsenja 1,04 m/s in poti drsenja 628 m pri različnih obremenitvah (3, 4 in 5) kg in pri volumenskem deležu delcev od 5–15 %. Rezultati kažejo, da ojačanje kovinske osnove z delci SiC in TiO_2 zmanjšuje obrabo pri sobni temperaturi. Rezultati tudi kažejo, da se obraba povečuje z večanjem obremenitve in daljšanjem poti drsenja. Koeficient trenja se zmanjšuje z obremenitvijo in z večanjem volumenskega deleža delcev za ojačanje. Trdota vzorcev hibridnega kompozita narašča z naraščanjem volumenskega deleža delcev SiC in TiO_2 za ojačanje. Pregled mikrostrukture je pokazal, da so delci SiC in TiO_2 enakomerno razporejeni v osnovi. Preiskava obrabljenih površin z vrstičnim elektronskim mikroskopom pokaže, da gre za mehanizem abrazijske obrabe zaradi trdih delcev, ki so na obrabljeni površini.

Ključne besede: obraba pri suhem drsenju, hibridni kompozit zlitine LM25Al, enak volumen SiC + TiO_2, mehanizem obrabe

1 INTRODUCTION

Metal-matrix composite materials are finding increasing numbers of applications in a variety of engineering fields due to their important properties. Hybrid composite materials are advanced composite materials reinforced with more than one substance in order to achieve a combined effect. This allows a rather high degree of freedom in the material design.[1]

The need for the light-weight and high-performance materials is increased day by day due to the increase in the application areas such as automotive, aerospace, deep-ocean, nuclear-energy-generation, structural applications, etc., that have led to the invention of hybrid materials in the form of composites.[2–5]

The studies on the wear of hybrid composite materials are necessary for the industry. An addition of hard particles to the matrix of a composite material influences the wear properties. The hard ceramic particles such as Al_2O_3, SiC, TiC, etc., embedded in the matrices of hybrid composite materials have shown to reduce the wear loss compared to the base alloys.[6–8] The studies indicated that the wear loss normally decreases with an increase in the hard-phase volume fraction and particle size.[9] The studies on the wear of composite materials indicated that the wear rate of Al_2O_3 reinforced composites decreases by two fold as the particle size increases from 5 μm to 142 μm at a fixed volume fraction.[10,11]

The results from the literature reveal that commonly only a single reinforcement is incorporated into a metallic matrix, but the recent trend involves hybrid reinforcements[12–14] enhancing the properties more than a single reinforcement.

There was an investigation of the factors influencing the dry-sliding-wear behavior such as the load, the sliding speed, the reinforcement content in an aluminium/fly ash/graphite hybrid metal-matrix composite and the results reveal that the load is the most significant parameter influencing the wear rate of the hybrid composite followed by the sliding speed and the reinforcement content.[14]

Asif et al.[15] conducted a comparative study made between binary and hybrid composites of an aluminium alloy reinforced with silicon carbide and an aluminium alloy reinforced with silicon carbide and graphite. Both composites were manufactured using the powder-metallurgy technique. The results from the pin-on-disc wear tester showed that the wear rate of the hybrid composite was lower than that of the binary composite. The results also indicated that the hybrid composite had an accepted level of tribological characteristics of the black and smooth worn surface.

For discontinuous metal-matrix composites, stir casting is generally accepted as a promising route, currently practiced commercially. Its advantage lies in its simplicity, flexibility and applicability to a large-quantity production. It is also attractive because, in principle, it allows the conventional metal processing route to be used, hence, minimizing the final cost of the product. This liquid-metallurgy technique is the most economical of all the available metal-matrix-composite productions[16] allowing an easy fabrication.

An important factor for the liquid-metallurgy technique is the solidification of the melt containing suspended dispersoids under a selected condition to obtain the desired distribution of the dispersed phase in the cast matrix. When preparing metal-matrix composites with the stir-casting method, there are several factors that need considerable attention, including the difficulty of achieving a uniform distribution of the reinforcement material, the wettability between the two main substances, the porosity of the cast metal-matrix composites and the chemical reaction between the reinforcement material and the matrix alloy. In order to achieve the optimum properties of a metal-matrix composite, the distribution of the reinforcement material in the matrix alloy must be uniform and the wettability or bonding between these substances should be optimized.

Discontinuous reinforced aluminium metal-matrix composites are a class of composite materials with desirable properties like low density, high specific stiffness, high specific strength, controlled coefficient of thermal expansion, increased fatigue resistance and superior dimensional stability at elevated temperatures.[17,18]

The sliding-wear behavior of a composite is found to be a function of many factors such as the volume fraction and particle size of reinforcement, the hardness and strength of the matrix alloy, applied load, environmental temperature, etc. The investigation of the sliding-wear properties of aluminium MMCs with the reinforcements such as SiC, Al_2O_3, TiC, TiB_2 and graphite was carried out by the researchers.[19–23] Recently, Vinoth et al.[24] have investigated the mechanical and tribological characteristics of stir-cast Al-Si10Mg and self-lubricating Al-Si10Mg/MoS_2 composites. They observed an improved wear resistance for Si10Mg/MoS_2 composites. A review of the literature indicated that most of the studies on the wear of metal-matrix composites are mainly focused on Al-SiC and Al-Al_2O_3 based composite systems. The wear properties of Al-TiO_2 indicate that the TiO_2 particles provide an excellent combination of mechanical and wear-resisting properties.

The aim of the present investigation is to evaluate the dry-sliding metal-metal wear behavior of the LM25 alloy, discontinuously reinforced with two different types of particles such as SiC and TiO_2. The stir-casting method was chosen for the manufacturing of hybrid metal-matrix composites. The effect of an equal volume fraction of the reinforcement and the applied load on the dry-sliding metal-metal wear behavior of the composite is investigated using a pin-on-disc wear tester. The hardness of the hybrid composite is measured to analyze the effect of the reinforcement.

The microstructure of the specimens is studied as the particle distribution and worn surfaces were examined with a scanning electron microscope.

2 MANUFACTURING OF THE HYBRID METAL-MATRIX COMPOSITE MATERIAL

Stir casting involves an incorporation of particles into the liquid aluminium melt, allowing the mixture to solidify. The crucial part of the fabrication is to create a good wetting between the particle reinforcement and the liquid aluminium-alloy melt. The simplest and most commercially used technique is stir casting or the vortex technique.[25] The vortex technique involves an introduction of preheated reinforcement particles into the vortex of a molten alloy created with a rotating impeller. Several aluminium companies adopted this technique at the commercial scale to achieve the homogeneity between the reinforcement particles and the moving solid-liquid interface during solidification.[26,27]

With the vortex method the matrix material is melted, stirred vigorously with a mechanical stirrer to form a vortex at the surface of the melt and the reinforcement material is then introduced at the side of the vortex. The process parameters such as the pouring temperature, the stirring speed and the preheating temperature of the reinforcement are suitably chosen.

About 1.6 kg of the LM25 alloy was melted in a graphite crucible in an induction-type electric-resistance furnace. The temperature of the melt was 825 °C. After the melting and degassing of the alloy by nitrogen a simple four-blade alumina-coated stainless-steel stirrer was introduced into the melt and the stirring was started. The depth of the immersion of the stirrer was maintained at about two-thirds of the depth of the molten metal.

During the stirring, the mixture of the preheated reinforcement particles of SiC and TiO_2 in equal volume fractions was added to the vortex formed due to the stirring. The reinforcement particles were preheated to

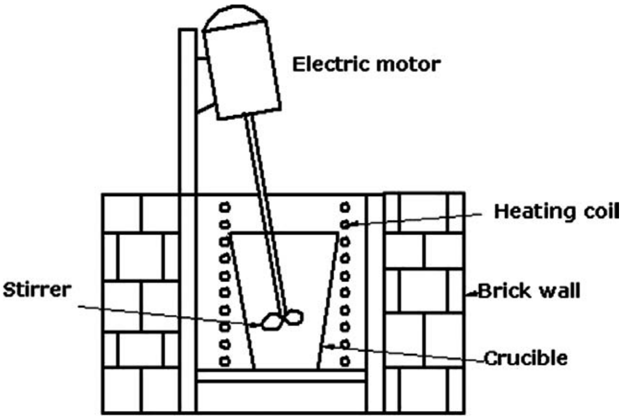

Figure 1: Stir-casting setup for MMC fabrication
Slika 1: Shematski prikaz izdelave MMC z vmešavanjem v talino

(a) (b) (c)

Figure 2: Manufactured composites with different reinforcements: a) 2.5 % SiC + 2.5 % TiO_2 = 5 %, b) 5 % SiC + 5 % TiO_2 = 10 %, c) 7.5 % SiC + 7.5 % TiO_2 = 15 %
Slika 2: Kompoziti z različnim deležem delcev za ojačanje: a) 2,5 % SiC + 2,5 % TiO_2 = 5 %, b) 5 % SiC + 5 % TiO_2 = 10 %, c) 7,5 % SiC + 7,5 % TiO_2 = 15 %

500 °C for an hour before the addition. Their average diameters were 25 μm and 50 μm, respectively.

After the complete addition of the particles into the melt, the composite material was tilt poured into the preheated (250 °C) permanent steel mould and allowed to cool in atmospheric air. The billet was then removed from the mould. LM25 hybrid composites with different volume fractions of the reinforcement material were thus produced and the wear specimens were made from them. A schematic view of the stir-casting setup is shown in **Figure 1**.The manufactured composites with different reinforcements are presented in **Figure 2**.

The nominal chemical composition of the LM25 aluminium alloy is presented in **Table 1**.

3 EXPERIMENTAL PROCEDURE

The sliding experiments were conducted at room temperature with a pin-on-disc wear-testing machine (wear and friction monitor TR-201). The pins were loaded against the disc by a dead-weight loading system. The pin specimen was flat ended with the 8 mm diameter and 20 mm length. The disc test piece was 100 mm in diameter and 10 mm in thickness. They slide on a disc with a diameter of 50 mm. The material of the disc is hardened steel of HV698. The wear tests of the composite specimens (LM25 + SiC & TiO_2) and unreinforced LM25 alloy were carried out under dry-sliding condition at three different applied loads of 29.43 N, 39.24 N and 49.05 N for a total sliding distance of 628 m at a constant sliding speed of 1.04 m/s. During the test the relative humidity and temperature of the surrounding atmosphere were about 50 % and 25 °C, respectively. The test duration was 10 min at a constant disc speed of 400 r/min for all the tests.

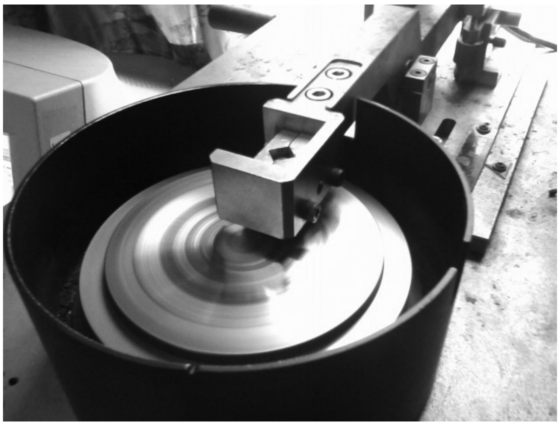

Figure 3: Photographic view of the pin-on-disc wear-testing machine
Slika 3: Posnetek naprave "pin-on-disc" za preizkušanje obrabe

The vertical height (displacement) of a specimen is continuously measured using a linear variable differential transformer (LVDT) with the accuracy of 1 μm during the wear test and the height loss is taken as the wear of the specimen. A photographic view of the pin-on-disc wear tester used in this investigation is shown in **Figure 3**. An experimental graph showing the height loss or wear in μm against the sliding time in seconds obtained with the wear testing is shown in **Figure 4**. The hardness of the composite material and LM25-alloy specimen at room temperature was measured using a Vickers hardness testing machine.

The sliding speed and the sliding distance covered by a test specimen on the complete course of the experiment or in a particular interval of time are calculated in the following way:

$$\text{Sliding speed} = \frac{\pi DN}{60{,}000}\ \text{m/s}$$

$$\text{Sliding distance} = \frac{\pi DNT}{60{,}000}\ \text{m/s}$$

where D = diameter of the wear track, N = disc speed in r/min, T = test duration in s.

Table 1: Nominal chemical composition of LM25-Al alloy (mass fractions, w/%)
Tabela 1: Nazivna kemijska sestava zlitine LM25-Al (masni deleži, w/%)

Element	Cu	Si	Mg	Mn	Fe	Ti	Ni	Zn	Sn	Al
Percentage	0.17	6.81	0.51	0.03	0.29	0.103	0.006	0.06	< 0.001	Balance

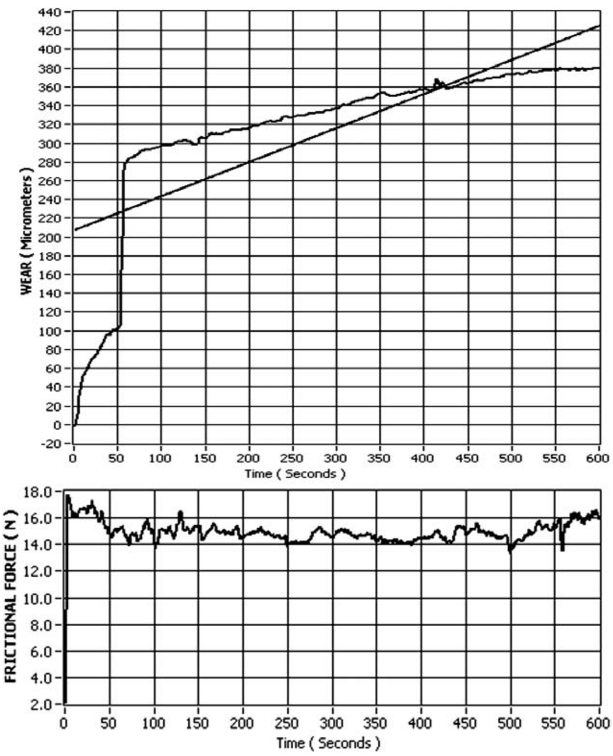

Figure 4: Typical graphical results from the pin-on-disc wear-testing machine: a) wear in μm and b) frictional force in N

Slika 4: Značilna grafična predstavitev rezultatov z naprave "pin-on-disc" za preizkušanje obrabe: a) obraba v μm in b) sila trenja v N

4 RESULTS AND DISCUSSION

The study on the wear of composite materials is very important for material scientists and manufacturing engineers. Especially when hybrid composite materials are used for a particular application, their response to wear is to be analyzed. The wear rate of hybrid composite materials is different from that of metallic materials because it consists of three different phases. In the present work the wear behavior of hybrid metal-matrix composites is analyzed and presented in detail.

4.1 Effects of the load and sliding distance on the wear rate

The wear of composite materials is analyzed using the wear performance graphs. The wear-test results for the (LM25 + SiC & TiO_2) composite and the unreinforced LM25-alloy specimen under dry-sliding conditions are presented in **Figure 5**. **Figure 5a** presents a variation of the wear rate with respect to the sliding distance for different volume fractions of the hybrid composite materials.

The graph exhibits two regions representing the running-in and steady-state periods. During the running-in period the wear rate increased very rapidly with the increasing sliding distance. During the steady-state period, the wear progressed at a slower rate and linearly with the increasing sliding distance. The higher wear rate at the initial stage was due to the adhesive nature of the sample on the sliding disc.[27] The results indicated that an increase in the sliding distance reduces the wear rate. The reason being that the increase in the sliding distance smoothens the surface of the composite material after 100 m, thus reducing the wear rate. **Figure 5b** shows a variation in the wear rate with respect to the sliding distance at a load of 39.24 N. The result obtained is almost similar to the result obtained before, but the increase in the load increases the wear rate of the

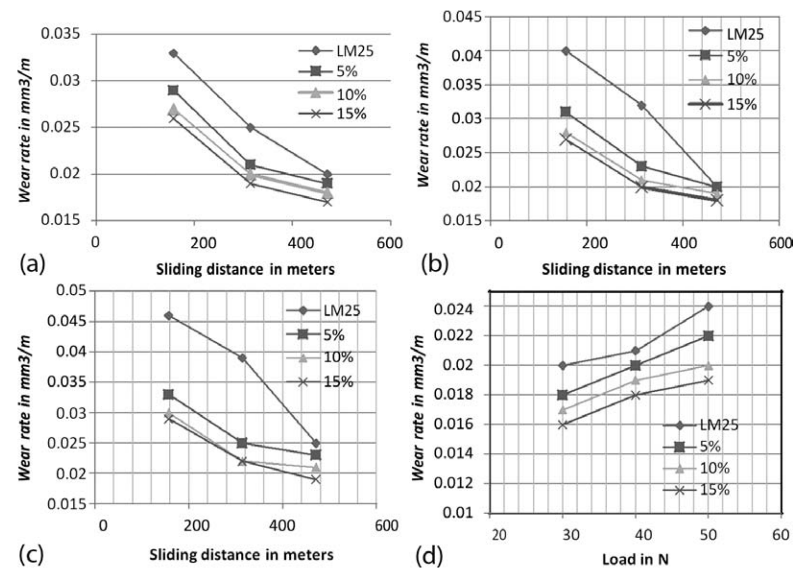

Figure 5: Wear rate of unreinforced alloy and composites at the applied loads: a) 29.43 N, b) 39.24 N, c) 49.05 N as a function of the sliding distance and d) at the end of the maximum sliding distance (628 m) as a function of the volume percentage of reinforcement

Slika 5: Hitrost obrabe neojačane zlitine in kompozitov pri izbranih obremenitvah: a) 29,43 N, b) 39,24 N, c) 49,05 N v odvisnosti od poti drsenja, d) na koncu maksimalne poti drsenja (628 m) v odvisnosti od volumenskega deleža delcev za ojačanje

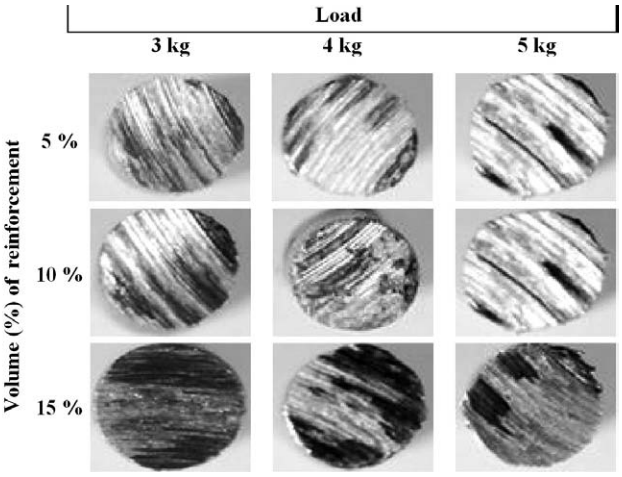

Figure 6: Photographs of the wear surfaces of the reinforced LM25-alloy composite specimens at the end of the maximum sliding distance

Slika 6: Posnetek obrabljenih površin ojačanih kompozitnih vzorcev zlitine LM25 na koncu maksimalne poti drsenja

composite material. **Figure 5c** shows the same trend as observed for the 29.43 N and 39.24 N loads. The general trend observed shows that an increase in the load increases the wear rate of the hybrid composite materials.

Figure 5d shows the variation in the wear rate with respect to the load and reinforcement volume for hybrid metal-matrix composites. The results are observed for the maximum distance of 628 m. The result clearly indicates that an increase in the load increases the wear rate. The maximum wear is also observed for the unreinforced alloy. The result clearly indicates that an increase in the reinforcement reduces the wear rate of hybrid metal-matrix composites. From the results it is clear that the particulate reinforcement of SiC and TiO_2 has a marked effect on the wear rate. The wear rate of a composite specimen decreases with the increasing volume percentage of the particulate reinforcement. As expected, the wear rate of a composite specimen with a fixed volume percentage of the reinforcement increases with the increasing load applied and it is depicted in **Figure 5d**. At a constant load a composite specimen shows a lower wear rate than the unreinforced alloy. The photographs of the wear surfaces of the reinforced aluminium-alloy specimens at the end of the maximum sliding distance for three different volume fractions are presented in **Figure 6**. The photographs reveal that the width of the scratches decreases with an increase in the volume content of the reinforcement and increases with an increase in the applied load. This is due to the resistance provided by the reinforcement (SiC + TiO_2) to the wear surface.

4.2 Effects of the load and sliding distance on the friction coefficient

The effects of the load and sliding distance on the friction coefficients of the unreinforced LM25 aluminium alloy and hybrid composite materials (SiC and TiO_2) with varying volume percentage of the reinforcement, obtained for the frictional force of the specimens during the sliding were plotted against the sliding distance and presented in **Figures 7a** to **7c**. From **Figure 7a**, it is clear that an increase in the sliding distance reduces the coefficient of friction. The reason for this is the fact that the additions of different compositions cause the composites to have a microstructural homogeneity, a greater porosity and a poor interfacial bonding between

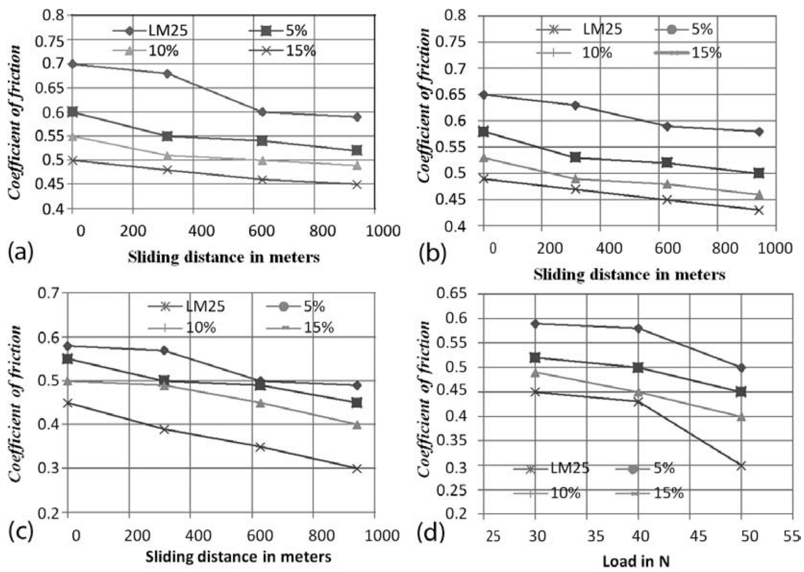

Figure 7: Coefficients of friction of unreinforced alloy and composites at the applied loads: a) 29.43 N, b) 39.24 N, c) 49.05 N and d) at the end of the maximum sliding distance as a function of the volume percentage

Slika 7: Koeficient trenja neojačane zlitine in kompozitov pri izbranih obremenitvah: a) 29,43 N, b) 39,24 N, c) 49,05 N, d) na koncu maksimalne poti drsenja v odvisnosti od volumenskega deleža the matrix and the TiO_2 particles.[27] **Figure 7b** shows a variation in the coefficient of friction with respect to the sliding distance at a load of 39.24 N. The result obtained is almost similar to the result obtained before, but the increase in the load did not lead to any clear change in the coefficient of friction. **Figure 7c** shows the same trend as observed for the loads of 29. 43 N and 39.24 N. The variations in the coefficient of friction versus the load for the hybrid metal-matrix composites indicate a reduction in the value of the coefficient of friction when the TiO_2 particles are incorporated, owing to a higher hardness of the TiO_2 particles.[20] **Figure 7d** shows a variation in the coefficient of friction with respect to the load. The coefficient of friction of both the LM25 alloy and its hybrid composite material including SiC and TiO_2 decreases with the increasing load and sliding distance. The coefficient of friction decreases linearly from 3 kg to 5 kg for both the matrix alloy and the hybrid composite. The coefficient of friction decreases in the range of 0.7–0.3. In general, for the LM25 alloy and all the hybrid composites, the friction coefficient decreases with an increase in the applied load.[6] The load has a significant effect on both the wear rate and the coefficient of friction. However, increasing the volume percentage of the reinforcement above 15 % at the applied load of 5 kg does not have a significant effect on the friction coefficient.[6]

4.3 Microstructural studies

The optical micrographs of the unreinforced LM25 alloy and its composites with (5, 10 and 15) % volume fractions of the SiC and TiO_2 reinforcement are shown in **Figures 8a** to **8d**. A microstructural analysis of the specimens indicated that that the SiC and TiO_2 particles are non-uniformly distributed in the matrix. The presence of porosity is seen around the SiC and TiO_2 particles. It is observed that there is more porosity around the TiO_2 particles than the SiC particles. The porosity of the specimens increases with the increasing volume fraction of the particulate reinforcement.

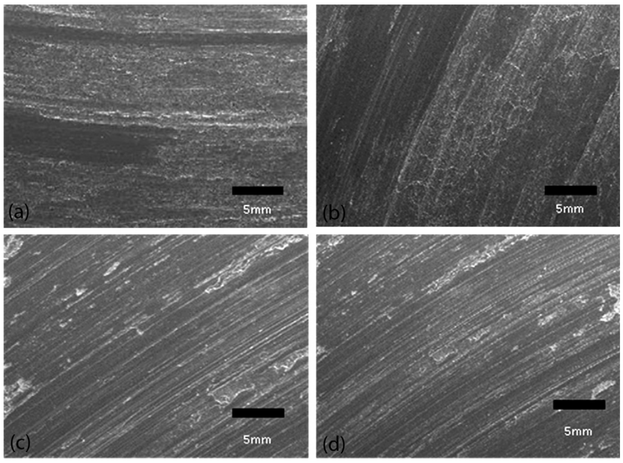

Figure 9: SEM photographs of the wear tracks: a) unreinforced alloy and composites with: b) 5 % (SiC + TiO_2), c) 10 % (SiC + TiO_2) and d) 15 % (SiC + TiO_2) volume fractions after the complete sliding distance with the maximum load of 5 kg

Slika 9: SEM-posnetki sledi obrabe: a) neojačana zlitina in kompoziti z volumenskim deležem: b) 5 % (SiC + TiO_2), c) 10 % (SiC + TiO_2) and d) 15 % (SiC + TiO_2) po celotni poti drsenja z maksimalno obremenitvijo 5 kg

Figure 9 shows the wear tracks observed on the surfaces of the hybrid composite materials. These SEM micrographs were taken at a scale of 5 mm. The graphs clearly indicate how the wear takes place on the top surfaces of the hybrid composite materials. The graphs

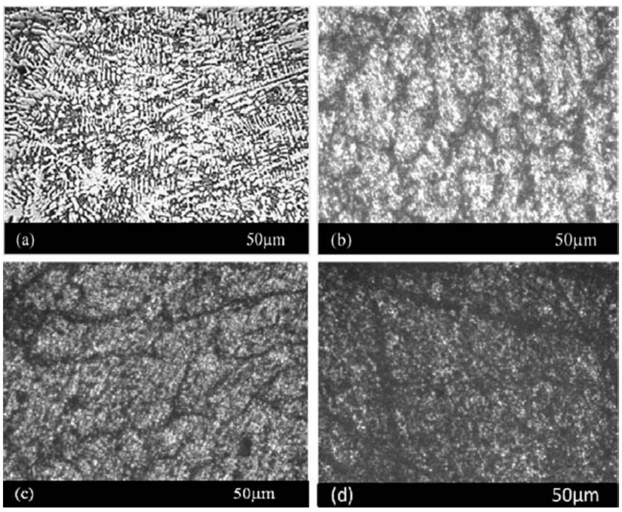

Figure 8: Light micrographs of: a) unreinforced alloy, b) LM25 + 5 % reinforcement, c) LM25 + 10 % reinforcement and d) LM25 + 15 % reinforcement

Slika 8: Mikrostruktura: a) neojačane zlitine, b) LM25 + 5 % delcev za ojačanje, c) LM25 + 10 % delcev za ojačanje in d) LM25 + 15 % delcev za ojačanje

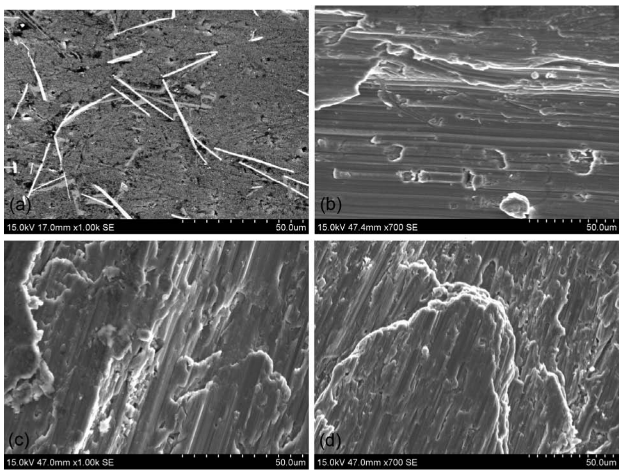

Figure 10: SEM photographs of the worn surfaces with 50-µm scale marker: a) unreinforced alloy and the composites with: b) 5 % (SiC + TiO_2), c) 10 % (SiC + TiO_2) and d) 15 % (SiC + TiO_2) volume fractions after the complete sliding distance with the maximum load of 5 kg

Slika 10: SEM-posnetki obrabljene površine: a) neojačana zlitina in kompoziti z volumenskim deležem: b) 5 % (SiC + TiO_2), c) 10 % (SiC + TiO_2) in d) 15 % (SiC + TiO_2) po celotni poti drsenja z maksimalno obremenitvijo 5 kg show that the wear pattern is stronger on the material without the reinforcement. An increase in the reinforcement reduces the wear and the surface observed is smooth.

Figure 10 shows that the composite material has a much rougher surface than the unreinforced alloy. The composite material exhibits cavities and large grooved regions on the wear surfaces and also contains ceramic particles in the cavities, some of them having been pulled out. In the case of the samples subjected to the 5 kg load the width of the grooves and the size of the dimples are greater than those on the surface worn by the 3 kg load. There is a change from a mild to a severe wear caused by an increase in the load due to a greater plastic flow on the sliding surface of the specimen under a higher load.[27] The composite material from **Figure 10b** was subjected to a severe wear and the one from **Figure 10d** was subjected to a mild

wear due to low or high reinforcements. Dimples are formed due to the removal of the material. The particle pull-out is due to the poor particle/matrix bonding.[27] This indicates the abrasive-wear mechanism of the composite material while resisting the delamination process. The wear resistance is larger in the case of the high volume percentage.

5 CONCLUSIONS

The investigation of the effect of the SiC and TiO_2 reinforcement on the wear behavior of the LM25-alloy hybrid composite led to the following conclusions:

As the load is increased, a change from a mild to a severe wear takes place much faster on the alloy than on the composites.

The wear rate decreases with the increasing volume content of the reinforcement.

The coefficient of friction decreases with an increase in the particle reinforcement and load (for the fixed-sized SiC and TiO_2 particulates).

The coefficient of friction and the wear rate of a hybrid composite are lower when compared with the matrix alloy and a binary composite.

The result of the scanning electron microscope shows that a composite alloy has a much rougher surface than the unreinforced alloy. This indicates the abrasive-wear mechanism which is due to hard ceramic particles embedded in the surface of the composite.

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