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WEAR BEHAVIOR OF Al/SiC/GRAPHITE AND Al/FeB/GRAPHITE HYBRID COMPOSITES

VEDENJE HIBRIDNIH KOMPOZITOV Al/SiC/GRAFIT IN Al/FeB/GRAFIT PRI OBRABI

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Silicon carbide is often the preferred reinforcement in the production of aluminium-powder composites. In this study, aluminium composites were produced with 10 % and 20 % silicon-carbide and ferroboron reinforcements and (0, 0.5, 1 and 1.5) % graphite additions using powder metallurgy. The effects of the reinforcement type, the amount and the graphite content on the wear resistance were investigated. When compared with the unreinforced aluminium sample, it was clear that the increasing reinforcement increased the wear resistance. It was determined that the increasing graphite content negatively affects the wear resistance. The sample including 20 % ferroboron and 0 % graphite showed the minimum wear rate.

Keywords: aluminum hybrid composite, ferroboron, silicon carbide, wear

Silicijev karbid se pogosto uporablja za ojačanje pri proizvodnji aluminijevih kompozitov iz prahov. V tej študiji so bili aluminijevi kompoziti izdelani po metalurgiji prahov, utrjeni z 10 %, 20 % silicijevega karbida, fero-bora in dodatkom (0, 0,5, 1 in 1,5) % grafita. Raziskani so bili vplivi vrste ojačitve, količine ojačitve in količine grafita na odpornost proti obrabi. V primerjavi z neutrjenimi vzorci aluminija je razvidno, da se odpornost proti obrabi povečuje z večanjem utrjevanja. Ugotovljeno je, da povečanje količine grafita negativno vpliva na odpornost proti obrabi. Najmanjšo stopnjo obrabe je pokazal vzorec, ki je vseboval 20 % fero-bora in bil brez grafita.

Ključne besede: aluminijev hibridni kompozit, fero-bor, silicijev karbid, obraba

1 INTRODUCTION

Powder metallurgy is considered as a good technique for producing metal-matrix composites[1] and has a wide range of applications ranging from automotive to advanced aerospace components[2]. P/M components are an established economic alternative to the components made with other manufacturing processes as well as the only means to produce those components that cannot be made with other methods[2]. One of the best properties of the composites fabricated with powder metallurgy is obtained when the reinforcement is homogeneously dispersed in the matrix, as proven with both experimental and theoretical studies[3]. Another advantage of the powder-metallurgy technique is the fact that it allows us to manufacture near-net-shape products at low costs[1].

Al-based particulate-reinforced metal-matrix composites have attracted much interest due to their potential use and desirable properties[4]. Aluminum is one of the best materials for the matrix because of its low density, high conductivity and high toughness. The other advantage of using Al for the matrices of MMCs is its corrosion resistance which is very important when using composites in different environments[3,5]. Aluminum P/M alloys are used in the automobile industry for cylinder liners, cylinder blocks and drive shafts, replacing more traditional ferrous alloys[6,7]. Moreover, Al composites are used for helicopter parts in aeronautics, such as the parts of the body, the support for rotor plates and rotor vanes in compressors[7]. Their use is a part of the trend toward the materials that can reduce the weight of a vehicle[6]. However, a low wear resistance of pure aluminum is a serious drawback in using it in many applications[1]. An addition of a non-metallic second phase such as oxides, carbides, nitrides and borides to aluminum alloys can dramatically improve the mechanical properties and wear resistance of the materials[8]. Particle reinforcements are more favorable than the fiber type as they allow a better control of the microstructure and mechanical properties obtained by varying the size and the volume fraction of the reinforcement[1].

Aluminium-matrix composites (AMCs) reinforced with SiC_P are recognized as important advanced structural materials due to their desirable properties, including a high specific stiffness, a high specific strength, a high temperature resistance and an improved wear resistance[9]. So, many studies were carried out on the preparation and wear properties of the Al-matrix composites with the SiC-particle reinforcements[10–13]. However, there are not many works on the wear behavior of the Al-matrix composites with the FeB-particle reinforcements. Generally, the effect of the FeB reinforcement on the wear properties was investigated for iron-based P/M alloys[14–17].

In addition to the contact configuration for different types of the wear tester, the wear behavior of materials is related to several factors such as the properties of the materials sliding against each other and experimental conditions including environmental conditions, load, speed, etc.[8] The wear rate and friction coefficient of an Al-matrix composite strongly depends on the reinforcement particles, the amounts of the reinforcement and graphite[12,13,18,19]. It was found that the wear rate of a hard-particle composite is substantially lower than that of the base material[7,20]. The reinforcement of an aluminum matrix with SiC or FeB was generally found to improve the wear resistance[7,14,21].

In this study, an aluminum-matrix composite with the reinforcement of SiC or FeB and an addition of graphite (Gr) particulates was explored for tribological properties. In many works, it was reported that graphite particulates form a solid lubricant on a tribosurface[19,22,23]. Generally, an addition of graphite to aluminum alloys is known to decrease the strength, fracture energy, ductility and hardness of the materials. A graphite particulate has a brittle structure; therefore, the tendency of crack initiation and propagation increases at the graphite-metal interface[19,22]. Also, the final properties of the metal-matrix composites depend on the matrix and ceramic reinforcements, the bonding of the ceramic reinforcements, the size and distribution of ceramic reinforcements and the graphite particulates in an aluminum matrix. According to the literature studies, little information about the effect of the FeB reinforcement and graphite particulates on the wear properties is available. In this work, the effect of the FeB reinforcement, the SiC reinforcement and graphite on the wear properties of P/M composites was investigated.

2 MATERIALS AND METHODS

2.1 Production of the composites

In this study Al/SiC/Gr hybrid composites with the size of Ø 20 mm × 10 mm were produced using the powder-metallurgy method. The chemical composition of the aluminium powder was 98.23 % Al–0.0056 % Fe–1.52 % MgO. The sizes of aluminium, FeB and SiC powders were below 53 μm.

Al/Gr composites were reinforced with SiC and FeB particles. The composites were produced with the additions of w = (0, 0.5, 1, 1.5) % graphite and w = (10, 20) % FeB or SiC (**Table 1**). The powder mixtures were pressed under a 400 MPa load, with the size of Ø 20 mm × 10 mm. The green samples were sintered at 620 °C for 1 h.

Table 1: Powder compositions of composite samples (mass fractions, w/%)

Tabela 1: Sestava prahov kompozitnih vzorcev (masni deleži, w/%)

Sample	Al	SiC	Gr	Sample	Al	FeB	Gr
1	90	10	0	9	90	10	0
2	89.5	10	0.5	10	89.5	10	0.5
3	89	10	1	11	89	10	1
4	88.5	10	1.5	12	88.5	10	1.5
5	80	20	0	13	80	20	0
6	79.5	20	0.5	14	79.5	20	0.5
7	79	20	1	15	79	20	1
8	78.5	20	1.5	16	78.5	20	1.5

2.2 Microstructural investigation

Microstructural examinations were carried out with SEM to investigate the porosities and particle clusters.

2.3 Density

The densities of the composite samples were measured according to Archimedes' principle and their porosity ratios were calculated.

2.4 Wear tests

A CSM instruments ball-on-disc wear-test unit was employed in the present work for a tribological analysis under dry-sliding conditions with the Al-SiC_p + Al-FeB_p composites against a 100 Cr6 stainless-steel ball. The stainless-steel counter-face material had a diameter of 6 mm. All the experiments were carried out at a load of 3 N at room temperature. Each test was performed with a sliding speed of 20 cm/s and the track diameter was 8 mm. The speed, temperature and sliding-distance conditions were all kept constant in each test. This procedure was executed for each sample along the total sliding distance of 250 m. The coefficient of friction was recorded during the wear testing by a transducer on the load arm of the tribometer. The quantitative value of the wear was obtained by measuring the cross-sectional area of the wear track and then the wear rate was calculated by the TRIBOX 2.10.C program.

3 RESULTS AND DISCUSSION

3.1 Microstructural investigation

It can be seen that SiC particles dispersed uniformly in the aluminium matrix (**Figure 1**). But in the FeB-reinforced samples, some clusters of FeB particles

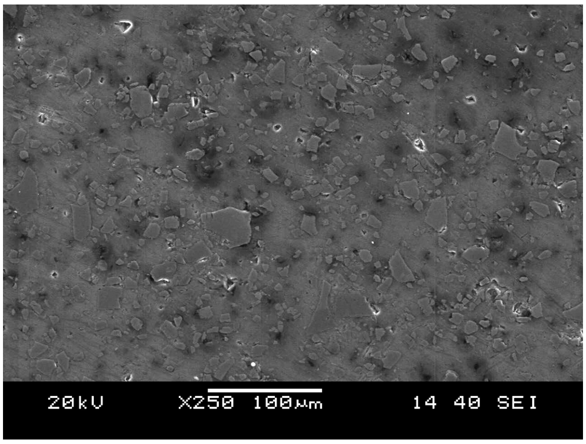

Figure 1: Microstructure of 10 % SiC + 1.5 % Gr reinforced composite

Slika 1: Mikrostruktura kompozita, ojačanega z 10 % SiC + 1,5 % grafita

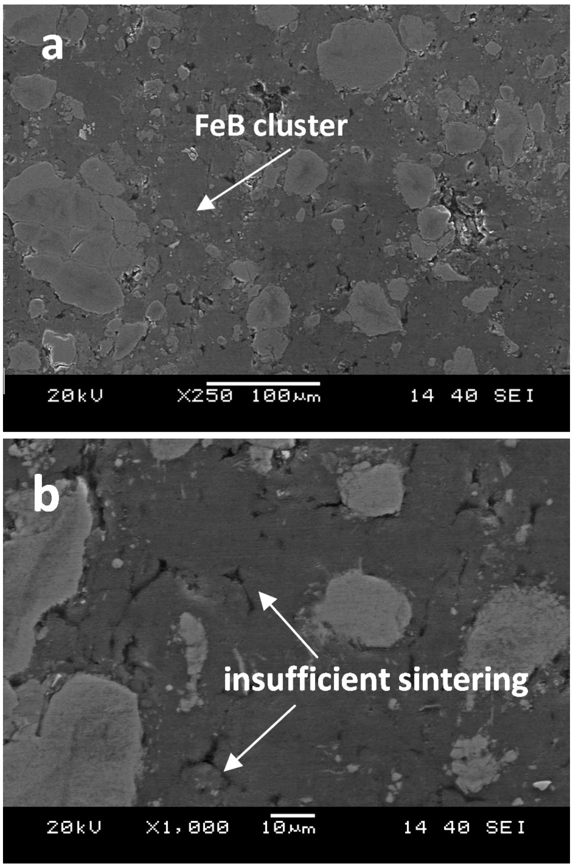

Figure 2: Microstructure of 20 % FeB + 1.5 % Gr reinforced composite: a) FeB cluster in the structure, b) porosities due to insufficient sintering
Slika 2: Mikrostruktura kompozita, ojačanega z 20 % FeB + 1,5 % grafita: a) skupek FeB v strukturi, b) poroznosti zaradi nezadostnega sintranja

were noticed (**Figure 2a**). The sample including 20 % FeB + 1.5 % Gr, exhibiting the maximum porosity, had pores around the reinforcements and also between the grain boundaries due to insufficient sintering (**Figure 2b**). In contrast, there were no pores around the reinforcement particles of the sample including 10 % SiC + 1.5 Gr which exhibited the minimum porosity (**Figure 1**); moreover, no insufficient sintering was confirmed. The maximum porosity was revealed in the sample with the maximum reinforcement. It is thought that the pores originating from insufficient sintering can result from the cold-pressing pressure. Due to the negative influence of an increase in the reinforcement on the compressibility, the sintering process for the sample reinforced with 20 % FeB + 1.5 % Gr was not adequately maintained. Moreover, the pores arising from the clusters must be considered.

3.2 Density

The compressibility of composite powders is noticeably lower than that of the unreinforced matrix, often producing a low green density and an insufficient strength to support secondary processing like sintering, machining or extrusion[4]. Reinforcement particles have a tendency to associate themselves with porosity and give rise to particle-porosity clusters[24]. The presence of nonmetallics such as unreduced oxides reduces the compressibility because of their hardness and low specific gravity[2]. Rahimian et al.[25] reported that as the amount of alumina increases, the relative density declines. The reason for this, in comparison with pure aluminum, is the decline in the pressing capacity of the samples with the increase in the amount of alumina. This is due to a higher hardness of alumina. Therefore, these composites have a lower compressibility resulting in a lower relative density[25]. In **Figure 3** it can be seen that the increasing amount of reinforcement has increased the porosity. SEM images of the microstructures show the increase in the porosity with the increasing reinforcement (**Figures 1** and **2**). Also, Tekmen et al.[24] found that the increasing reinforcement volume fraction increases the porosity content. In the present study the porosity ratio of the unreinforced aluminium composite was calculated as 3.77 %. So, the minimum porosity ratio compared to the reinforced samples was shown. It was observed that the composites with an addition of FeB have a higher porosity compared to the SiC samples. During the microstructural investigation, agglomerations of FeB particles were noticed particularly in larger reinforcement amounts (**Figure 2a**). The SiC-reinforced composites showed a more homogeneous distribution in the aluminium matrix. So, it was concluded that a particle agglomeration causes an increase in the porosity.

In general, the porosity due to the increasing graphite amount exhibited a downward trend except for the composites reinforced with 20 % FeB (**Figure 3**). Due to the FeB clusters (**Figure 2a**), the graphite could not properly show its lubricant effect during cold pressing.

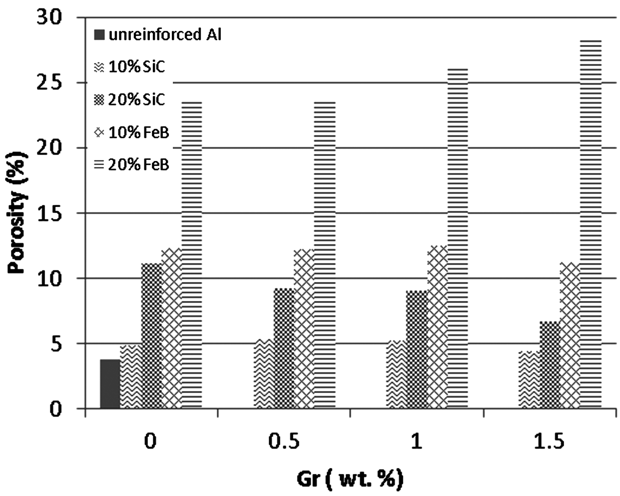

Figure 3: Porosity values of the composites (*w*/%)
Slika 3: Delež poroznosti kompozitov (*w*/%)

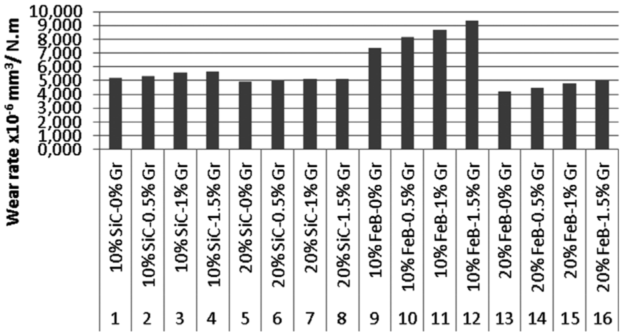

Figure 4: Wear rate
Slika 4: Hitrost obrabe

3.3 Wear tests

From **Figure 4**, it can be concluded that the maximum wear rate was obtained for the sample consisting of 10 % FeB + 1.5 % Gr and the minimum wear rate was obtained for the sample without graphite and reinforced with 20 % FeB. The wear-test parameters generated a very large wear scar on the unreinforced aluminium, so that the profilometer could not scan the whole section of the wear scar. For this reason, the wear rate of the unreinforced aluminium composite could not be calculated; however, it can be said that the unreinforced aluminium shows a higher wear rate than the reinforced ones.

The wear resistance increased as the reinforcement proportion increased from 10 % to 20 % since the hard SiC and FeB particles in the matrix resisted the counterpart. The increased reinforcement reduced the contact area between the counterpart and the relatively soft matrix, thus the abrasion (wear) was reduced. **Figure 5** explains this phenomenon. Here, the hard SiC particles outcropped and formed an impediment for the contact between the composite surface and the counterpart (**Figure 5a**). The outcropped particles abraded the counterpart. **Figure 6** also shows the abraded areas of the counterparts of the 10 % FeB + 1.5 % Gr and 20 % SiC + 0 % Gr composites. The counterpart of the 20 % SiC + 0 % Gr composite exhibited a larger abrasion area in comparison with the counterpart of 10 % FeB + 1.5 % Gr due to the increased reinforcement amount. Ravindran et al.[26] reported that the dispersion of silicon carbide, the hard phase in the soft aluminium matrix, tends to reduce the wear loss of hybrid composites.

In the literature some researchers maintain that the graphite amount in aluminium composites enhances the tribological properties and wear resistance[13,27,28]. However, Vencl et al.[29] reported that an addition of graphite particles (w = 1 %) to a composite with SiC parti-

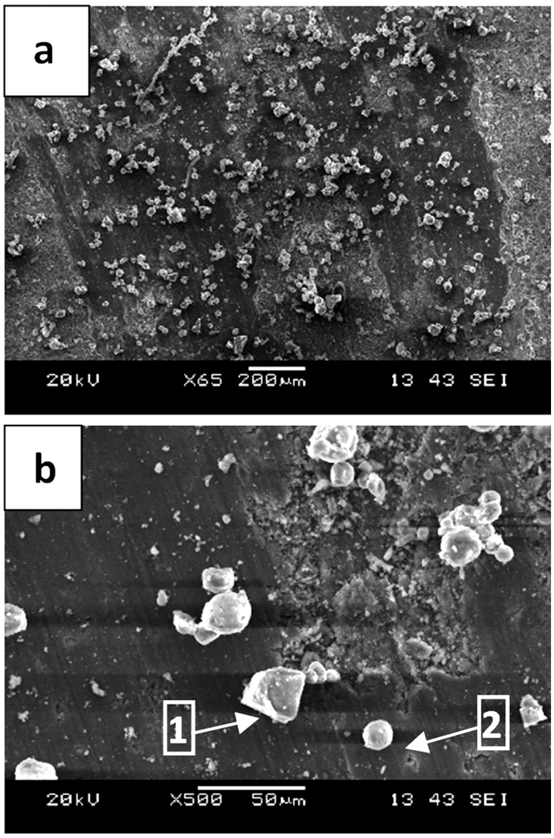

Figure 5: Wear surface of 20 % SiC + 0 % Gr reinforced composite: a) wear tracks, b) EDX analysis
Slika 5: Obrabljena površina kompozita, ojačanega z 20 % SiC + 0 % grafita: a) sledi obrabe, b) EDX-analiza

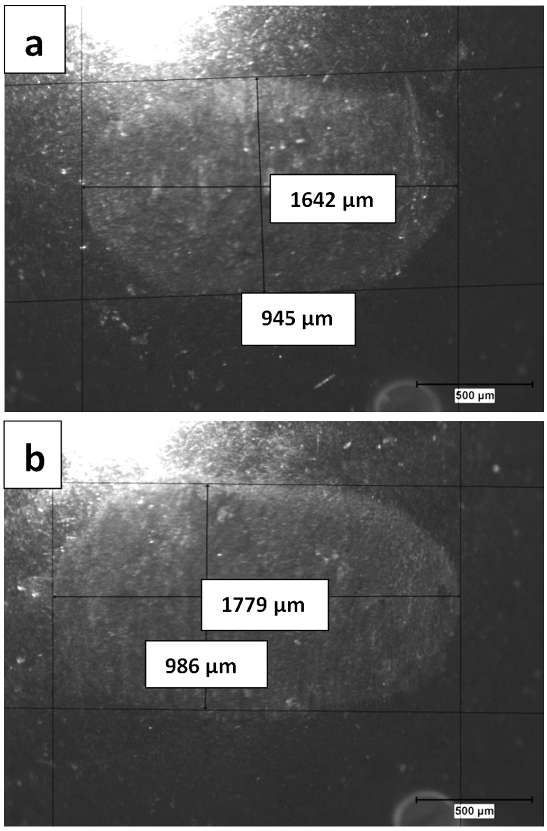

Figure 6: Counter parts of the composites: a) 10 % FeB + 1.5 % Gr, b) 20 % SiC + 0 % Gr
Slika 6: Stična površina kompozitov: a) 10 % FeB + 1,5 % grafita, b) 20 % SiC + 0 % grafita

cles further reduced the wear rate and the coefficient of friction, but this influence of such a relatively small amount of graphite was not clear enough and should be considered only as a trend of behavior. According to the results of the present study, the increased Gr amount increased the wear rate. Actually, this was an expected result because the main reason for the graphite addition to aluminium composites reinforced with hard particles was to simplify the machining. The presence of the hard, brittle and abrasive SiC reinforcement makes the material difficult to form or machine using traditional manufacturing processes. In order to improve the machinability of the SiC_p/Al composites, graphite was added to the composites[30].

As an alternative approach, an explanation for the decreasing wear rate with the increasing reinforcement might be the pores filled up with the wear debris. A high reinforcement amount causes high porosity, so the wear debris could easily fill these numerous pores instead of being pushed out of the tribological system. Actually, a negative effect of the increasing pores on the wear resistance was expected. In this case, the pores presumably filled with the wear debris gave rise to a decrease in the wear rate calculated as the volumetric wear loss. As can be seen from **Figure 7**, a pore on the worn surface of the 20 % FeB + 0 % Gr hybrid composite was filled with the wear debris. According to the results of the EDX analysis it can be concluded that wear debris is composed of the aluminium matrix, the stainless-steel counterpart and FeB-reinforcement particles (**Table 2**).

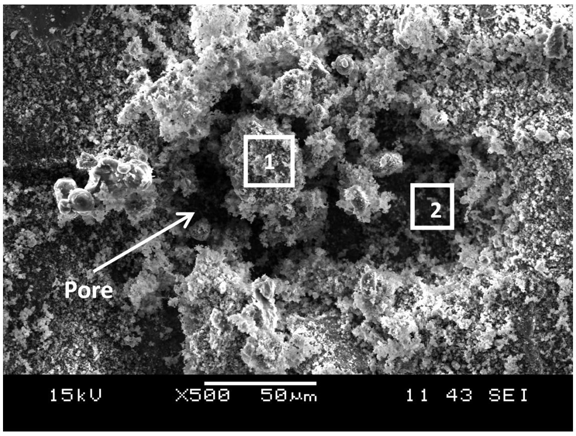

Figure 7: Pore and wear debris on the worn surface of 20 % FeB + 0 % Gr hybrid composite

Slika 7: Praznine in delci obrabe na obrabljeni površini hibridnega kompozita z 20 % FeB + 0 % grafita

Table 2: EDX analysis of the pore on the worn surface of 20 % FeB + 0 % Gr hybrid composite (*w*/%)

Tabela 2: EDX-analiza površine pore na obrabljeni površini hibridnega kompozita z 20 % FeB + 0 % grafita (*w*/%)

Element	Al	Fe	Cr	Si	Mn
1	81.799	13.687	3.542	0.203	0.769
2	76.015	18.834	4.319	0.172	0.661

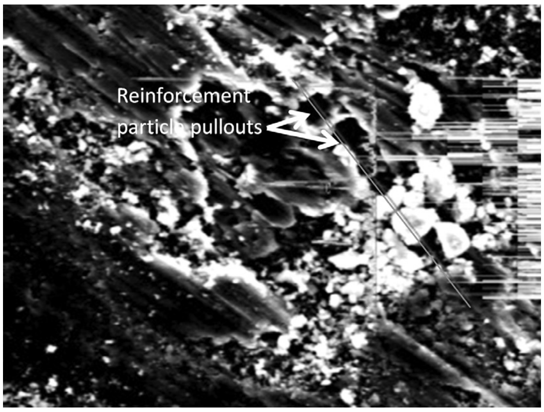

Figure 8: EDX analysis of 10 % SiC + 1.5 % Gr hybrid composite along the line; left: Si, right: C (graphite)

Slika 8: Linijska EDX-analiza hibridnega kompozita z 10 % SiC + 1,5 % grafita; levo: Si, desno: C (grafit)

The pores could have been formed due to the insufficient sintering (**Figure 2**) and they could have also been created by the mechanical force during the wear test. **Figure 8** shows the pores caused by the wear test, as the reinforcement particles were pulled out. These kinds of pores could be large and easily filled with the wear debris. The reason for the particle pullout was found with the EDX analysis carried out along a line. The EDX graph of graphite shows a significant increase of the pores arrowed as "reinforcement particle pullouts" in **Figure 8**. By means of the EDX analysis (in **Figure 8**, the EDX graph on the right-hand side shows graphite) it was realized that the wall of pores was smeared by graphite, so the wettability between the matrix and the reinforcement was reduced. In this case, the particle pullout occurred easily and due to the low bonding of the aluminium matrix and the reinforcement. Thus, a detrimental effect of graphite on the wear resistance was confirmed.

The samples that exhibit the maximum wear rate in both groups, the SiC- and FeB-reinforced composites, exhibit both abrasive and adhesive wear tracks. For both reinforcement groups, if the wear surfaces of the most and the least wear-resistant samples were compared, adhesion wear was observed to be more intense on the least wear-resistant samples.

The wear surface of the sample reinforced with 10 % SiC + 1.5 % Gr exhibited both large craters arising from adhesion and abrasion scratches (**Figure 9a**). Similarly, the wear surface of the sample including 10 % FeB + 1.5 % Gr shows adhesion craters and also flaky wear debris subjected to delamination (**Figure 10**). According to the EDX analysis (**Table 3**) the aluminium amount of the delaminated area was larger than the other analyzed area; consequently, it is maintained that the delaminated part had a smaller reinforcement amount and was subjected to a large plastic deformation. The plastically deformed part became strain hardened and brittle. Ravindran et al.[26]

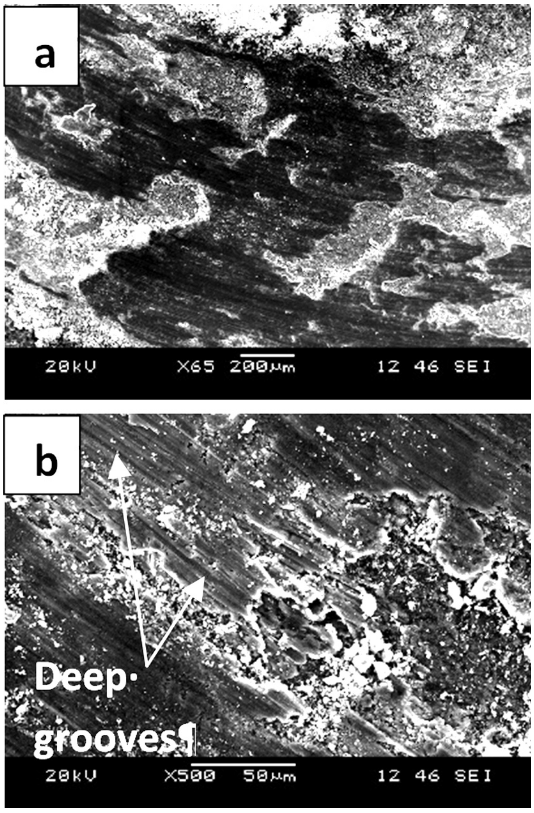

Figure 9: Wear surface of 10 % SiC + 1.5 % Gr reinforced composite: a) abrasion and adhesion marks, b) deep abrasion grooves

Slika 9: Obrabljena površina kompozita, ojačanega z 10 % SiC + 1,5 % grafita: a) obraba in lepljenje, b) globoki abrazijski utori

also observed severe plastic deformation of the Al 2024 matrix and a brittle fracture on the wear surface.

Table 3: EDX analysis of 10 % FeB + 1.5 % Gr reinforced composite (*w*/%)

Tabela 3: EDX-analiza kompozitov, ojačanih z 10 % FeB + 1,5 % grafita (*w*/%)

Element	Al	Fe	Cr	C	Si	Mn
1	93.197	4.631	1.259	0.352	0.188	0.374
2	88.810	6.680	1.628	1.184	1.069	0.630

If the wear surfaces in **Figures 9** and **11** are compared, it can be observed that the adhesive-wear tracks reduced and the abrasive scratches became shallower with the increase in the reinforcement proportion from 10 % to 20 %. Similar observations were made for the wear surfaces of the FeB-reinforced samples (**Figures 10** and **12**).

On the wear surfaces of the most wear-resistant samples including a 20 % reinforcement of (FeB or SiC) + 0 % Gr, it was observed that the reinforcement particles were pulled out but not taken away from the tribological system (**Figure 9**). It is maintained that the detached hard reinforcement particles might have become embedded a little into the soft matrix due to the applied load during the wear test and decreased the wear rate by reducing the real contact area between the surface

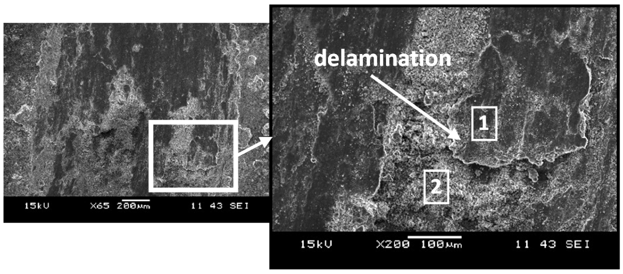

Figure 10: Wear surface of 10 % FeB + 1.5 % Gr reinforced composite

Slika 10: Obrabljena površina kompozita, ojačanega z 10 % FeB + 1,5 % grafita

and the counterpart. As can be seen from the EDX analysis (**Table 4**), the particle marked as "1" is the FeB reinforcement covered with some of the Al matrix (**Figure 12**). Similarly, the pulled-out SiC particle marked as "1" and the presumably oxidized aluminium particle marked as "2" were detected with EDX as presented in **Table 5** and **Figure 9**.

The shape of the reinforcement particles caused a difference in the abrasive-wear tracks, particularly for the 10 % reinforced samples. The sharp and angularly shaped SiC particles caused narrow but deep grooves (**Figure 9**), while the relatively round-shaped FeB particles formed shallower and wider grooves (**Figure 11**).

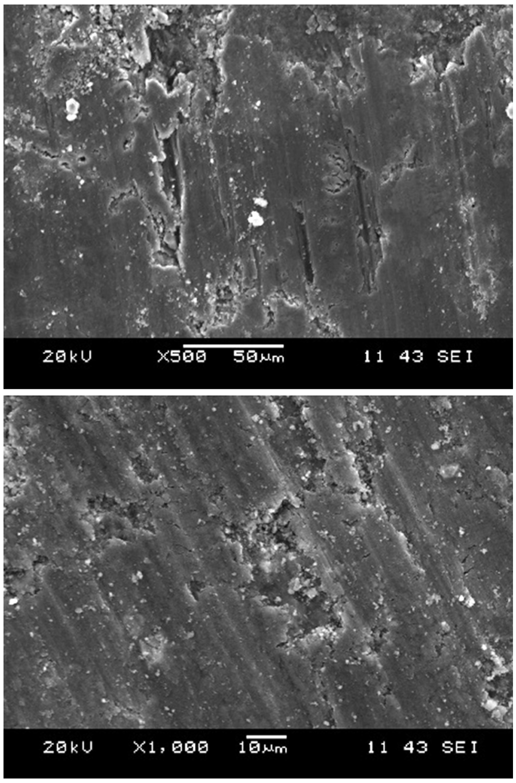

Figure 11: Wide and shallow wear tracks of 10 % FeB + 1.5 % Gr reinforced composite

Slika 11: Široke in plitve sledi obrabe na kompozitu, ojačanem z 10 % FeB + 1,5 % grafita

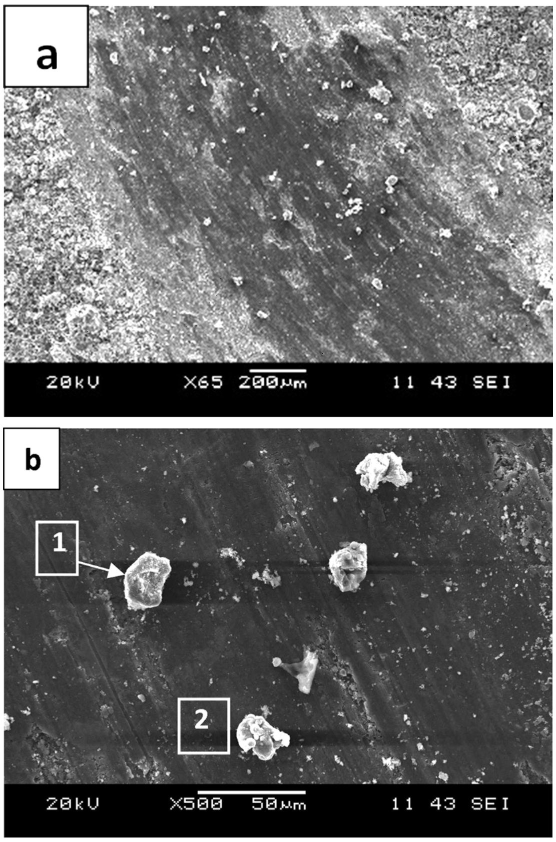

Figure 12: Wear surface of 20 % FeB + 0 % Gr reinforced composite: a) wear tracks, b) EDX analysis
Slika 12: Obraba na površini kompozita, ojačanega z 20 % FeB + 0% grafita: a) sledi obrabe, b) EDX- analiza

Table 4: EDX analysis of 20 % FeB + 0 % Gr reinforced composite (*w*/%)
Tabela 4: EDX-analiza kompozitov, ojačanih z 20 % FeB + 0 % grafita (*w*/%)

Element	Al	Fe	Cr	C	Si	Mn
1	67.211	29.460	1.326	0.030	0.945	1.027
2	79.865	17.242	1.994	-	0.459	0.441

Table 5: EDX analysis of 20 % SiC + 0 % Gr reinforced composite (*w*/%)
Tabela 5: EDX-analiza kompozitov, ojačanih z 20 % SiC + 0 % grafita (*w*/%)

Element	Al	Fe	C	Si	O
1	0.860	0.220	26.665	71.914	0.341
2	91.952	0.202	3.615	1.020	3.210

As the two surfaces are brought in contact, the nanoscale asperities are the first to come into contact, instantly plastically deforming and merging to form micro- or macro-contacts, which, upon further application of the load, may deform due to elastic or elastic-plastic deformation[31]. A further plastic deformation leads to a brittle fracture. In this study, the sample including only 20 % SiC exhibited brittle flakes during the wear test. Here, the plastically deformed aluminium matrix underwent strain hardening. The brittle layer consisted of

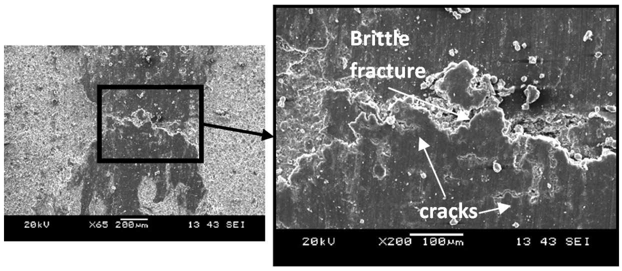

Figure 13: Brittle wear-debris structure on the wear surface of 20 % SiC + 0 % Gr reinforced composite
Slika 13: Krhki odkruški na obrabljeni površini kompozita, ojačanega z 20 % SiC + 0 % grafita

the strain-hardened aluminium and the hard SiC particles were smeared on its surface. In **Figure 13**, the cracks and debris separated from the brittle layer can be seen. It is assumed that the existence of SiC particles contributes to the strain-hardened aluminium and so the hardness of the strain-hardened matrix increases further.

Analyzing the EDX results of the 10 % FeB + 1.5 % Gr and 20 % FeB + 0 % Gr reinforced samples (**Tables 3** and **4**), some elements such as Cr and Mn belonging to the stainless-steel counterpart were observed. In contrast, the EDX result for the 20 % SiC + 0 % Gr reinforced composite did not show any element of the stainless-steel counterpart (**Table 5**).

4 CONCLUSIONS

- The minimum wear rate was obtained for the sample without graphite and reinforced with 20 % FeB.
- The 20 % FeB-reinforced samples showed the maximum porosity and insufficient sintering due to the increased reinforcement. In a further study, pressure can be raised during cold pressing.
- The maximum wear rate was obtained for the sample consisting of 10 % FeB + 1.5 % Gr.
- The increased graphite amount increased the wear rate of all the Al-powder composites.
- The increased reinforcement increased the porosity.
- The wear rate decreased with the increasing reinforcement.

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