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Wear performance of aluminium/Al_2O_3/C hybrid composites

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ABSTRACT

Purpose: The effects of the applied load and graphite volume fraction on dry-sliding friction and wear properties of hybrid composite reinforced with alumina fibres and graphite in form of fibres or flakes were investigated.

Design/methodology/approach: The tests were carried out on preforms with about 6.5 to 15.0 % (all the percentages v/v) of Al_2O_3 fibres (Saffil) and 1.5to 12.0 % of graphite, infiltrated using the squeeze casting method. Porous preforms possess suitable permeability, good strength and reveal semi-oriented arrangement of fibres and graphite flakes. The composite microstructure exhibit regular arrangement of fibres and rather poor bonding between matrix and graphite.

Dry wear tests were carried out using a wear tester at constant sliding velocity and under various loads, which in relation to diameter of specimens corresponds to pressure of P_1 = 0.81; P_2 = 1.23; P_3 = 1.53 MPa.

Findings: Comparison of wear losses for monolithic Al-Si7 alloy and its composites reveals that alumina fibres considerably improve this property but addition of graphite also protects from seizure. The composites reinforced with graphite fibres were less sensitive to the applied load than both the matrix and the composites reinforced with graphite flakes.

Research limitations/implications: Proposed method can be used for manufacturing of hybrid composite with graphite fibers less than 10 vol. % due to problems with producing of the uniform microstructure.

Practical implications: Aluminum casting alloys can be locally reinforced to improve strength and wear resistance in wide temperature range.

Originality/value: Article is valuable for persons, that are interesting in production of casting composite materials reinforced with hybrid ceramic perform. Proposed method allows incorporate graphite into composite reinforced with Al_2O_3 fibers (Saffil)

Keywords: Composites; Graphite; Wear resistance

MATERIALS

1. Introduction

The cast composite materials reinforced with fibres or particles show a relatively large variety with regard to their structures and properties. They are usually characterised by good mechanical properties in a wide temperature range and significant wear resistance. Application of graphite as one of the reinforcing components permits creating a film separating the wearing couple without any additional lubricant. This effectively prevents adhesive tacking, temperature increase and seizure [1,2,3,4]. The performed research works are usually aimed at defining the wear mechanism and optimum graphite content, and at determining the extent to that the tribological parameters (usually pressure and velocity) affect the wear intensity.

The flake graphite almost always reduces the friction coefficient, disintegrates the wear products, accelerates heat abstraction and increases seizure resistance [5,6]. Although

Table 1.
Specification of of Saffil alumina short fibres and graphite components.

Materials	Composition (wt.%)	Density (g/cm^3)	Tensile strength (MPa)	Young's modulus (GPa)	Diameter (μm)	Length (mm)
Saffil fibre	Al_2O_3-δ: 96-97 SiO_2: 2-4	3.3	2000	300	2-4	0.1-0.3
Graphite fibre	C:>99.9	1.8-2.0	1960	340	9-10	1-2
Graphite flakes	C:>99	2.26		12		

increased wear resistance can be observed in most cases [7,8], a limit graphite content should be considered, over that the matrix becomes weaker and the properties are reduced [9,10].

As revealed in the so far performed research, the fibre graphite increases wear resistance [11,12] and using a hybrid preform of Al_2O_3 and C fibres contributes to improvement of mechanical properties, also at elevated temperatures [13].

When analysing the mechanism of dry-sliding wear of composites, one should consider the so-called composite effect that consists in two opposite factors influencing the wear resistance. The first one is weakening the matrix by graphite, which dominates up to ca. 5.0 % of graphite content [9], and the coupling between graphite and matrix, resulting among others from the strongly anisotropic nature of the graphite thermal expansion coefficient [14].

The often referred wear mechanism is spalling or delamination. As a result of significant deformation, a morphologically distinct structure is created in the upper layer during the friction process. The material there is mechanically mixed with the wear products (MML = mechanically mixed layer), usually with broken fibres, matrix particles or even with the counterpart material [11,12]. If the stresses between the unimpaired material inside and that surface layer exceed some critical values, spalling takes place.

The presence of other fibres, e.g. Al_2O_3, could effectively prevent the matrix deformation, to carry the load and lock the microcracks that often develop along the friction direction. It seems that integrity of the wear surface and spalling of the surface layer is a basic factor influencing wear resistance of composite materials containing graphite.

2. Examined material

The porous ceramic preforms were infiltrated with the EN-AC AlSi7Mg alloy by the direct sqeeze casting method. For the squeeze infiltration process, a 60-tonne hydraulic press was used. The preform was put into a mould pre-heated to 200 - 240 °C and infiltrated by metal under the pressure of 75 MPa. The pressure was maintained for 10-20s during solidification. Mould was vented to remove all gases from porous perform The ceramic preforms were made of Saffil fibres provided by Saffil Ltd, UK. Fibres were mixed with graphite flake and fibres manufactured by SGL Carbon Company, Nowy Sacz, Poland. The graphite flakes Els-395, fraction 0.062, were of fractional purity. The dia. 10 μm fibres made on the polyacrylonitrile precursor basis contained at least 99.99 % C, see Table 1. To bind the fibres and give the preform the durability required to bear the pressure of liquid metal stream, a silica-based binder was used, which with increasing temperature reaches the irreversible and durable crystalline variation – the tridymite [15, 20].

Microscopic examination revealed no wetting of graphite by the used silica-based binder. The binder spreads on the Al_2O_3 fibre surface, but in contact with graphite makes drops proving much larger wetting angle, see Fig. 1. The possible cracks or defects in the laminar graphite structure can be the places of the binder infiltration and favour creation of strong joints. However, it is most probable that graphite gets fixed in the weave of Al_2O_3 fibres and the required preform strength results from relatively strong joints between the fibres. In the case of fibre graphite, it was difficult to mix the components properly and obtain finally a homogeneous composite structure. The preforms were characterised by lower durability and adding more graphite became impossible. Because graphite, especially in form of flake, oxidizes readily above 500°C so inert atmosphere of argon during burning of perform at 950°C was applied . The performs exhibit a semi-oriented structure, with a disorderly arrangement of the fibres and graphite in plane, whereas the fibres are partially ordered in the transverse direction. For examination, the preforms containing 6,5 to 15 % of Al_2O_3 fibres (Saffil), 2 to 13 % of flake graphite and 2 to 5 % of short graphite fibres were prepared.

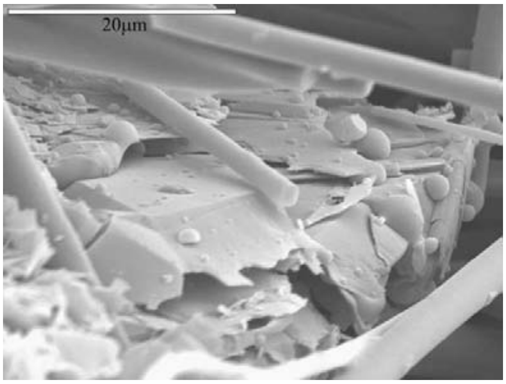


Fig. 1. Fracture of a preform with graphite flake and binder drops on it

For the wear resistance tests, the dia. 8 mm specimens were prepared, which were pressed against a steel counterpart moving reciprocally (Fig. 2). The applied forces resulted in pressures P_1 = 0.81; P_2 = 1.23; P_3 = 1.53 MPa. The counterpart was made of tool steel CT70 of 67 HRC. The average velocity of 0.92 m/s was equal for all the tests. The wear measurements were taken after 2500 m of friction distance. Before each measurement, the wear surface was ground with abrasive paper 1200 and washed with acetone.

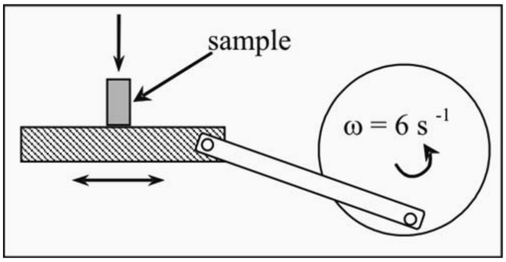


Fig. 2. Diagram of the tribological test stand

Specimens (8mm x 20mm) for microstructral examination were prepared by standard metallographic techniques. After the wear tests were sectioned parallel or perpendicular to the abraded surface, mounted in polyester resin, polished and sometimes etched. Metallographic specimens were examined in a optical and scanning electron microscope.

3. Results

The graphite addition is detrimental to strength and permeability of the preforms. With increasing graphite content, permeability decreases ca. 30 %, down from ca 90 $10^{-6}m^2$/Pa s for a graphite-free preform to ca. 65 units for the preforms containing 8.1 % of graphite. This can be detrimental to infiltration conditions and contribute to creation of the composite defects, like porosity, gas porosity or the preform deformation.

Observations of fracture surfaces revealed complete infiltration by the liquid alloy. In spite of lower permeability of the graphite-containing preforms, no significant increase of porosity was observed. There were no visible residues of the matrix on graphite flakes on the fracture surface, what can suggest a very weak joint between graphite and matrix, see Fig. 3.

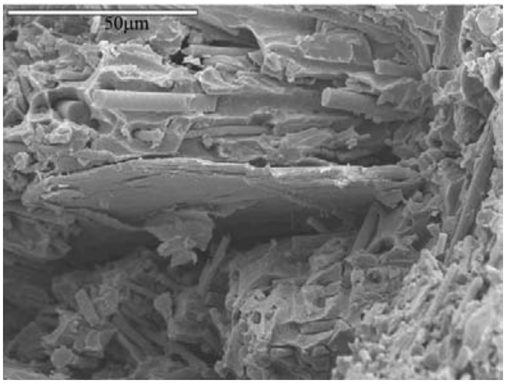


Fig. 3. Fracture of the composite with a graphite flake

However, the planned reinforcing effect of the matrix weakened by graphite flakes was reached. The small bridge over a wrinkled single graphite flake, indicated with an arrow in Fig.4, was reinforced with Al_2O_3 fibres. It can be anticipated that possible abrasion of a specimen with such microstructure will be restrained by these fibres.

Under high load when temperature increases, plastic deformation of matrix occurs and tribolayer begins to develop rigid alumina fibres should reduce such phenomena. Though due to various defect existed at matrix-reinforcement interface microcracks may easily nucleate under the tribolayer and induce the delaminating process.

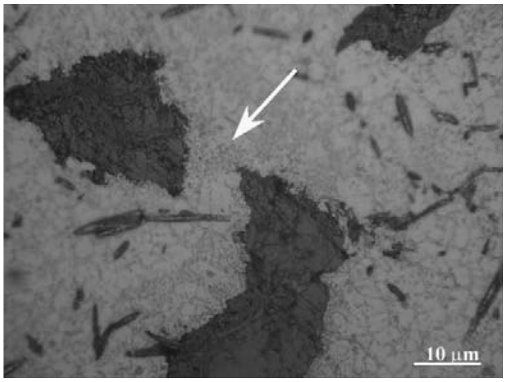


Fig. 4. Microstructure of hybrid composites with the view of party uncovered single graphite flake

The composite material structures were also observed directly after casting and after the T6 heat treatment consisting in solutioning and ageing. Since condition of graphite and possibility to create acicular Al_4C_3 precipitates is important for these materials, the ageing time at 540 °C was prolonged to 20 hours and the graphite form was observed every 2 hours. No degradation of graphite or its reaction with the matrix was found.

Observations of the specimens in as-cast condition showed uniform distribution of fibres in the matrix and partially diversified distribution of graphite. During preparation of the preforms, the flake graphite is susceptible to segregation, but the fibre graphite is hardly subject to mixing with the Al_2O_3 fibres. The changes implemented in subsequent stages of the work permitted partial restriction of these phenomena, see Fig 5.

Measurements of HB hardness of the composites proved that both the Al_2O_3 fibres and graphite strengthen the matrix, see Table 2. Hardness of the composite containing only Al_2O_3 fibres was 90 units and after adding flake graphite it ranged between 85 and 97, depending on the percentage. The composites containing 10 % of Al_2O_3 and 5 % of fibre graphite were characterised with the highest hardness of 112.

Table 2.
Hardness HB

Material	Average hardness HB
Matrix AlSi7Mg	66
AlSi7Mg-10% Al_2O_3	90
10% Al_2O_3+5% C_{fl}	95 (85-97)
10% Al_2O_3+5% C_{fibre}	105 (104-112)

The initial tribological examination of specimens of the alloy with no reinforcement, reinforced with Al_2O_3 fibres only or with the Al_2O_3 fibres and graphite, revealed distinct differences in the wear and the way in that the friction couple was wearing. In the case of unreinforced specimens made of the matrix alloy, even at the lowest pressures (0.81 MPa) particles of the aluminium alloy were torn out and adhered to the counterpart. In spite of the so unfavourable co-operation of the friction couple, a quantitatively low wear of the unreinforced specimen was observed, see Fig. 6. Presumably, this is contributed by hard precipitates of silicon, present in the alloy.

Reinforcing the matrix with Al_2O_3 fibres gave the specimens higher coherence and counteracted plastic deformation of the sliding surface. This resulted in a respectively lower wear and improved collaboration of the friction couple, but also in erosion and faster wear of the counterpart.

The specimens reinforced with Al_2O_3 fibres and graphite performed decidedly better in dry-sliding conditions. The form of the created graphite film dependent on pressures, Al_2O_3 fibre content and graphite did not guarantee complete separation of the friction couple.

Fig. 5. Microstructure of hybrid composite material reinforced with Al_20_3 and graphite fibers

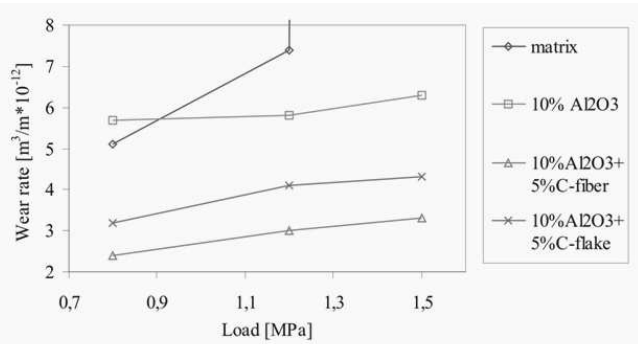


Fig. 6. Effect of pressure on wear of unreinforced alloy, composite with 10 % of Al_2O_3 fibres, composite with 10 % of Al_2O_3 fibres and 5 % of graphite fibres, composite with 10 % of Al_2O_3 fibres and 5 % of graphite flakes at P_2 = 1.35 MPa

Analysis of wear measurements of the specimens containing fibre graphite proved that the composite wear increases with increasing pressure. The higher fibre content, the more the specimen is sensitive to those pressures. A specimen containing 4.6 % C at 1.5 MPa revealed similar wear as the unreinforced alloy at lower pressure of 1.2 MPa. It can be found that, in order to create the material with the best wear resistance, the fibre graphite content should not exceed 3 %. Fig. 7 shows wear functions of the specimens containing 1.9 - 2.7 - 4.6 % of graphite fibres and 8 % of Al_2O_3 fibres.

Next tests reveal that optimum content of graphite due to wear properties depends on alumina fibre content. For example to improve effectively wear resistance of specimens containing 13-15% of alumina fibres the best volume graphite content amounts 5-6%.

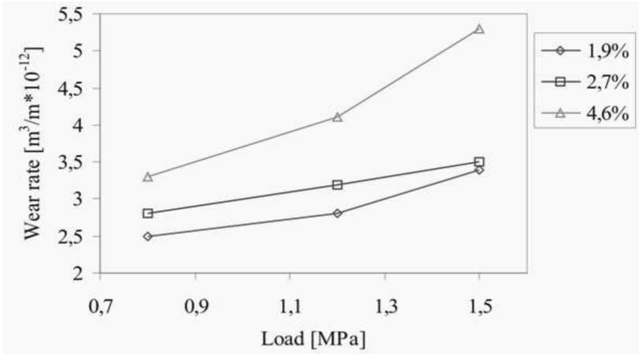


Fig. 7. Effect of pressure on wear of composite with constant 8 % of Al_2O_3 and 1.9 - 2.7 - 4.6 % of graphite fibres

The specimens with graphite in form of flakes showed a slightly other susceptibility to pressures. Their wear intensity was similar to that found in the specimens with higher content of graphite fibres. Increase of wear was especially visible in the specimens abraded under the pressure P_3 = 1.5 MPa, see Fig 8. The composites with 4.8 % of graphite showed better wear resistance and load had no major effect on the wear ratio.

It should be emphasized, that the role of graphite and its influence on the wear rate is strictly related to the content of alumina fibres. With a change of fibre content, the effect of graphite in function of load also changes. With increased alumina fibre content, the effect of pressure on the wear rate declines, the curves get flattened and assume the nature of constant functions.

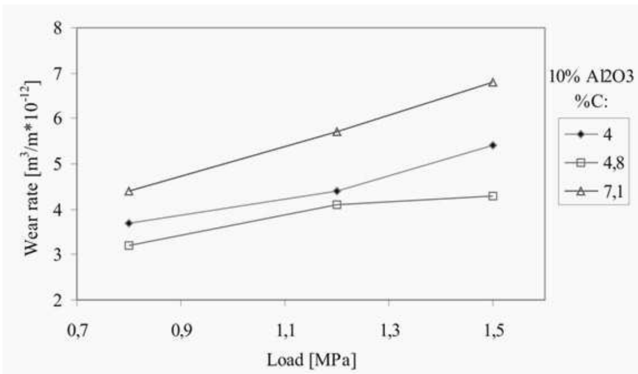


Fig. 8. Effect of pressure on wear of composite with constant 10 % of Al_2O_3 and 4.0 – 4.8 – 7.1 % of graphite flakes

At the subsequent stage of the research, a series of specimens reinforced with the same volume of graphite and different amount of Al_2O_3 fibres was prepared. With respect to wear resistance, 5.5 % of C was assumed as the optimum amount. Changes of Al_2O_3 fibre amount in the range of 6.3 to12.1 % resulted in small differences of wear results, see Figure. Although the specimens containing 6.3 and 11.3 % of fibres exhibited best properties, the results ranged within the error limits and were difficult to be interpreted, see Fig 9.

Generally it can be said that, at the assumed optimum graphite content of 5.5 %, the amount of fibres within the test ranges has no significant effect, while the pressure results in almost linear, 50-% increase of the wear lost for the entire series.

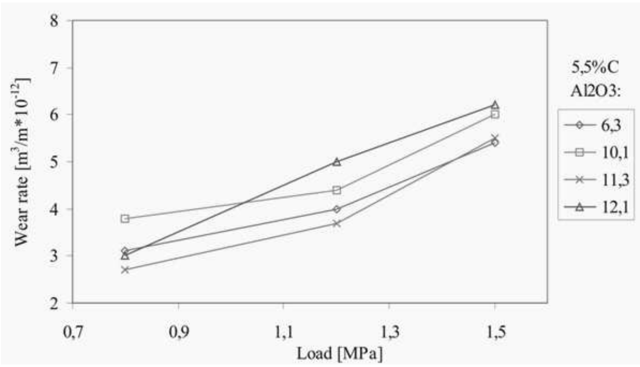


Fig. 9. Effect of pressure on wear of composite with constant 5.5 % of graphite flakes and 6.3 – 10.1 – 11.3 – 12.1 % of Al_2O_3 fibres

Wear surface analysis of hybrid composites were examined by optical and SEM microscope. Fig. 10 represents overall wear surface of specimens containing 1.9 % of graphite fibres and 6,5 % of Al_2O_3 fibres at various load, 0.81, 1.35 MPa. Also wear surface of specimens containing 13.6 % of graphite flakes and 7,4 % of Al_2O_3 at the same magnification are shown in Fig. 11.

Generally, both composites show almost similar behaviour. Under small load, 0.81MPa, mild damage of wear surface in both composites are found. The abrasion with grooving of the composites seems to be progressed by the fracture of reinforcement. Next deformation of matrix with fragments of alumina fibres due to the high friction force applied in the wear surface leads to severe surface damage. It can be considered that pocket of graphite which release solid lubricant also act as a weak spots and deteriorate the wear resistance of composites especially at high load.

At the low load the damage regions on the wear surface are reduced as shown in fig. 10a and 11a. Grooves in 13.6 % of graphite flakes and 7,4 % of Al_2O_3 are more distinguished that in composites reinforced with graphite fibres. Probably due similar characteristic of C fibres to Al_2O_3 fibres graphite in such form restrain plastic deformation. Wear surface indicate that the abrasive wear with intensive oxidization is the dominant wear mechanism at low applied load.

Wear surfaces at the load, 1.53 MPa, are shown in Fig. 10b and 11b. More local eroded areas are observed owing to the high load which easier uncovers graphite pockets and next pushes into it, under high pressure, wear debris. The grooves and crater regions in the worn surface of composite worn under higher load are clearly differ. For composites with graphite flakes craters are larger and cover more areas.

In [16] the crater regions were found to have more Fe (from counterparts) than in the smooth surface. It was suggested that some of these craters resulted from delamination in the wear surface. Wear debris having high Fe content is pushed into craters and mixed to form the mechanically mixed layer.

On the other hand iron oxide producing lubricating effect lowers friction coefficient and results in a lower wear rate [17]. Probably under higher load and increasing temperature both plastic deformation of the matrix and fracture of reinforcement generate mechanically mixed layer which can be easily delaminated.

a)

b)

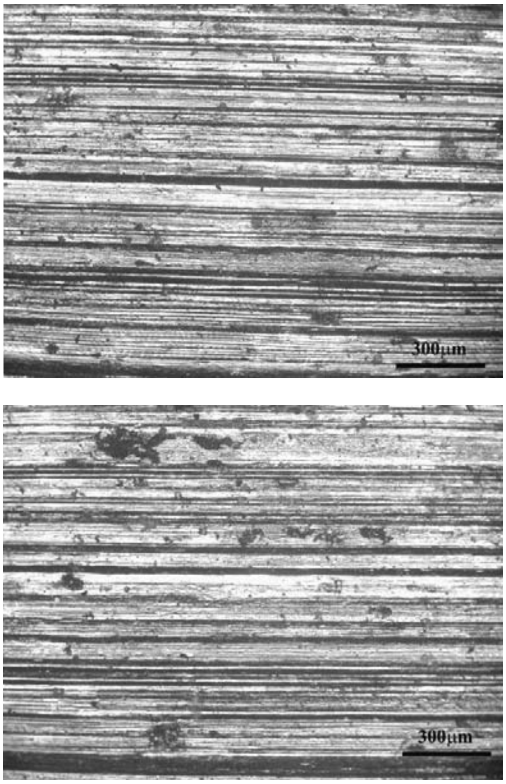


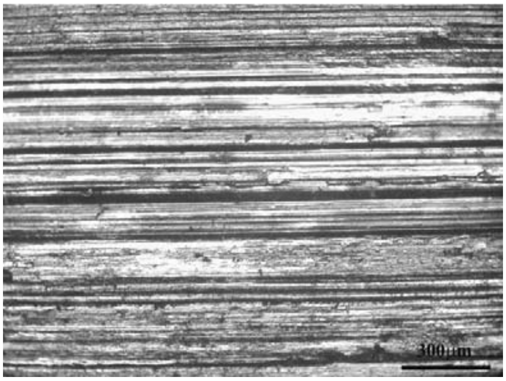
Fig. 10. Overall wear surface of composites containing 1.9 % of graphite fibres and 6,5 % of Al_2O_3 at 0.81 MPa load (a), and 1.35 MPa load (b).

Microscopic observations of friction surface were carried out, as well as of polished sections in the transverse and parallel planes, seeking to determine the effect of graphite on the specimens' wear.

Observations of polished specimens containing fibre graphite did not reveal pulling out the fibres even at lower pressures. It is only after polishing that a slight pulling out of fibre ends arranged at small angle to the polished surface happened. More often, breaking of fibres, disintegration and smearing on the friction surface was observed, see Fig 12a. Crushing of fibres occurred also deep from the friction surface, creating a sort of erosion centre. Unlike the graphite fibres, the Al_2O_3 fibres broke and their fragments were stuck into the surface and moved deep inside, maybe as a result of the MML phenomenon referred to in the literature [11,12,18,19].

The wear process was a bit different in the case of the specimens with flake graphite. Initially, the thin matrix layer above graphite was breaking along the abrasion direction and then it came to uncovering the graphite-filled pockets. The process of smearing out the graphite was slower at lower pressures and it basically consisted in replacing the graphite with a mixture of the wear products. Like in the case of fibre graphite, the created crater was an initial erosion centre. The so weakened microareas, if located along the abrasion direction, joined to initiate the grooves, see Fig 12b, dashed line.

a)



b)

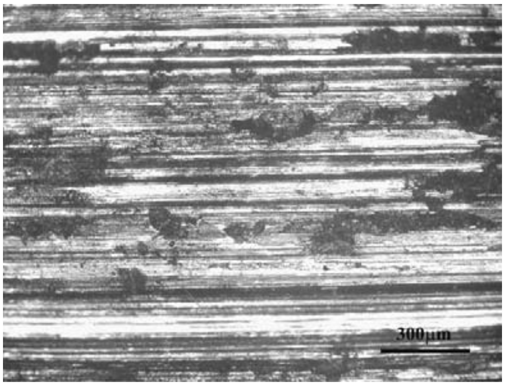
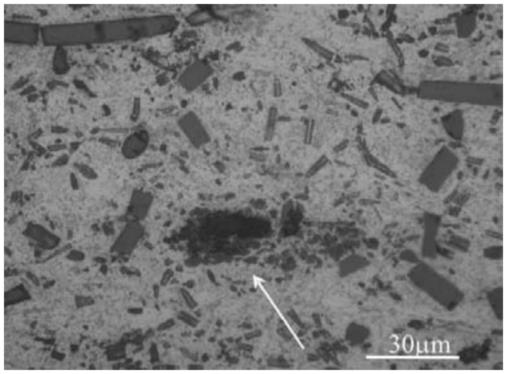


Fig. 11. Overall wear surface of composites containing 13.6 % of graphite flakes and 7.4 % of Al_2O_3 at 0.81 MPa load (a), and 1.35 MPa load (b)

Observations of polished specimens prepared in the plane perpendicular to the friction surface after 2500 m of friction distance revealed creation of the upper layer containing large amount of mixed fragments of fibres and wear products. That layer, weakened and distinct with respect to its structure, could next separate, significantly accelerating the wear process, see Fig. 13.

Under high pressures, covering and crusting of the developed cavities filled with debris could be seen, caused by intensive plastic deformation of the matrix, After a time, the formed scales cracked, uncovering the previously created cavities, see Fig 14a and b. Thereby, the debris was frequently shaped as thin plates.

a)



b)

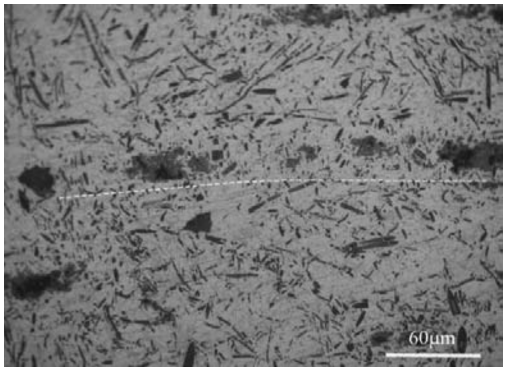


Fig. 12. View of a crumbled graphite fibre (a), connection of the erode places along the wear direction (b)

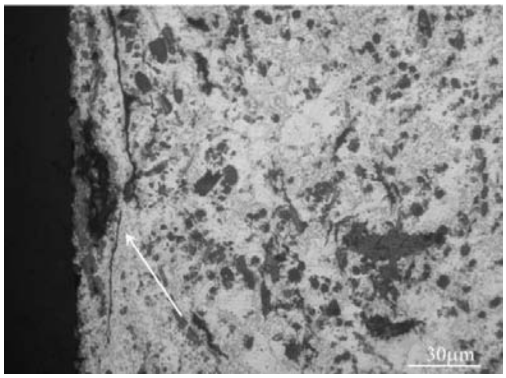


Fig. 13. View of a crack below the upper layer

Roughness of the counterpart surface was also measured, after wear testing against the unreinforced, reinforced with Al_2O_3 fibres only and hybrid graphite-containing specimens.

Profile examination as well as analysis and determination of all typical parameters describing roughness were performed by means of a profilegraphometer made by Hobson. Before each test, the steel counterpart plates were polished, so that the initial roughness R_a amounted to 0.4 - 0.6.

Fig. 15 shows an example of surface profile of the counterpart after the tests with three different specimens. Results obtained under 0.8 MPa load were compared, because only at this load it was possible to perform a complete test with a unreinforced specimen.

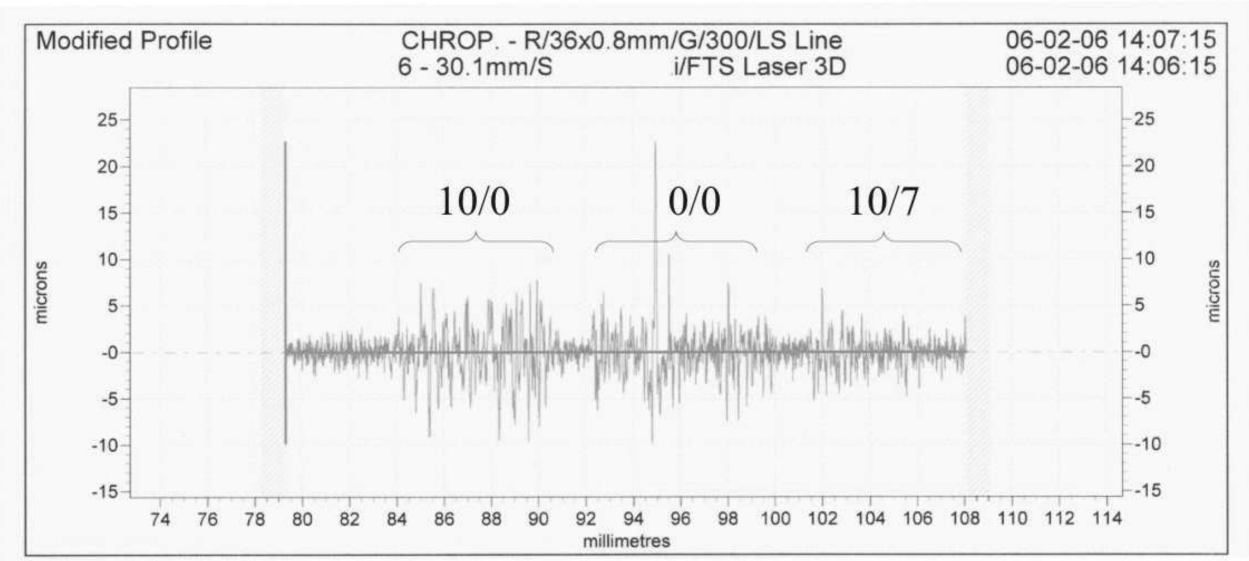
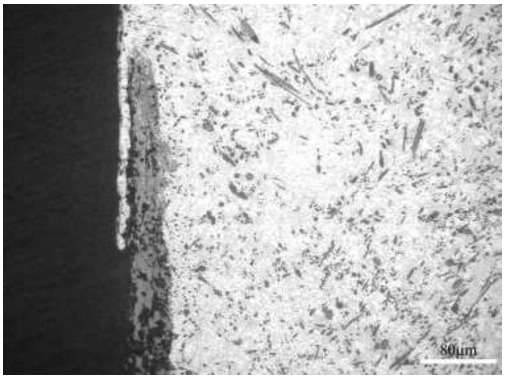


Fig. 15. Profile of counterpart after test with composite, unfreinforced alloy and hybrid composite

a)



b)

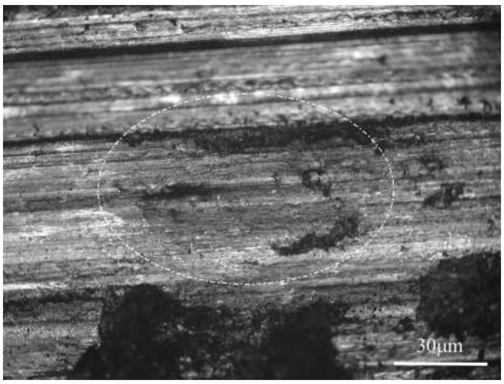


Fig. 14. Covering of cavity with debris (a), crack of scale over closed cavity (b)

Starting from the left side, the unworn surface area can be seen, next a trace after mating the composite specimen, the matrix specimen and finally the hybrid specimen containing 15 % of Al_2O_3 fibres and 5 % of C. In the case of $AlSi_7Mg$ matrix specimen, local adhesive welding of small particles occurred on the surface of the counterpart due to slight seizure. Therefore, it is possible that determination of the R_a parameter on the base of such profile takes into account these protrusions and does not reflect the real counterpart roughness.

In the measurements, the most representative profiles were chosen to avoid areas with seizures. The calculated R_a parameters listed in Table 3 show that, after abrasion against a specimen unreinforced or reinforced only with Al_2O_3 fibres, roughness is similar although scatter of the results for the first type specimen is larger. A clearly lower counterpart roughness was observed after the test with hybrid material marked with the symbol "10/7". The R_a parameter was half as large but it increased slightly in comparison to the initial roughness. Visually, the wear trace was shiny and possible defects, like e.g. grooves, were produced by hard debris particles contained in the graphite film.

Table 3.
Average roughness Ra

Specimen	symbol	Ra
counterface		0.4-0.6
AlSi7Mg matrix	0/0	2.0-4.5
10 vol. % Al_2O_3 AlSi7Mg	10/0	2.1-2.6
10 vol. % Al_2O_3 7 vol.% C_{flake} AlSi7Mg	10/7	0.8-1.4

4. Summary

Composite materials reinforced with Al_2O_3 fibres and graphite, featured by sufficiently homogeneous structure, were subject to microscopic examination, HB hardness measurements and wear resistance measurements. A hardness improvement was observed as a result of adding both Al_2O_3 fibres and graphite. With this respect, the composites containing 10 % of Al_2O_3 and 5

% of graphite fibres were characterised by the highest hardness of 112 HB. In the wear resistance tests, the effect of graphite content was determined, as well as of pressure of the specimen against the counterpart moving reciprocally. In most cases, higher pressure results in more intensive wear and the released graphite separates the friction couple less and less effectively. During friction, irrespective whether the graphite is in form of flakes or fibres, the wear products are forced in its place, which enlarges the erosion centres. Reinforcing the matrix with Al_2O_3 fibres impedes this process, allows more effective use of graphite and significantly moderates the wear.

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