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Wear mechanisms of fibre reinforced composite materials based on 2024 and 7075 aluminum alloys

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Materials

ABSTRACT

Purpose: Determination of fibre reinforcement influence on wear rate and wear mechanisms were examined. Moreover, effect of fibre orientation and specimen pressure on the counterpart were analyzed.
Design/methodology/approach: Composite materials based on 2024 and 7075 aluminium alloys were reinforced with 10-20 vol. % of alumina Saffil fibres and additionally choosen specimens with graphite fibres. Wear tests were carried out on pin-on-disc device where the specimens were pressed to the cast iron counterpart with forces corresponding to pressures of 0.8, 1.2 and 1.5 MPa.
Findings: Wear mass loss for composite materials reinforced only with Saffil Al_2O_3 fibres decreased with increase of fibre content in the matrix. The largest wear rate in relation to the unreinforced alloy exhibited composites containing 20 vol. % of Saffil Al_2O_3 fibres, tested under the largest applied pressure of 1.5 MPa. The graphite fibres enhance the wear resistance of composite materials under all applied pressures. The lubricant medium originated form worn graphite fibres prevented composite from seizure and adhesive wear.
Research limitations/implications: Fragmented alumina fibres acting as loose debris can enhance the wear rate both composite and iron counterpart. At high volume of graphite fibres produced preform possess low strength caused by weak joints between fibres.
Practical implications: Composite 2024 and 7075 materials reinforced with hybrid preforms produced from alumina and graphite fibres exhibit good wear resistance.
Originality/value: Manufactured composite materials will be considered as the friction materials for the high duty brakes.
Keywords: Composite materials; Dry sliding; Alumina fibres; Graphite fibres

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1. Introduction

Aluminum matrix composite materials reinforced with ceramic fibres usually exhibit high strength in wide temperature range, good wear properties and good thermal stability. For machine parts severe loaded composite materials with superior wear resistance could be very useful. During friction, reinforcement improving load-bearing capacity and thermal stability of metal matrix acts as a barrier for plastic deformation.

Usually at the some depth under the wear surface strongly loaded reinforcement, especially fibres, may crack and further mix with the matrix. These fragmented reinforcement and matrix component effect in work hardening of the matrix close to the wear surface, which is normally layer of 15-80 μm thickness [1,2]. On the other hand with increase of the contact temperature the matrix may undergo softening and recrystallization. Finally, it can result in the transition from mild to severe adhesive and then to molten wear [3]. Though fragmented reinforcement transferred during friction to the counterparts may work as abrasive material but usually prevent from melt wear and seizure [1,3,4].

At dry sliding condition when wear process proceeds slowly, surface layer with significantly changed microstructure and chemical composition is formed. This layer is described as Mechanically Mixed Layer (MML) and includes wear debris formed from grey iron compounds from the counterpart, the reinforcing phases, oxides and atmosphere gases [1,5]. MML is unstable and its thickness increases at low reinforcement fraction and at high loads [1,6]. Under cyclic plastic deformation cracks can develop parallel to the surface in the subsurface layer, which start from various types of defects at the reinforcement/matrix interface. The resulting delamination uncovers intact base material of the specimen, providing next portions of debris between the wearing surfaces.

Transport of debris observed in both directions between the specimen and the counterpart can be considerably reduced by producing a lubricant film. In the case of graphite, the created film has thickness of less than of 0.1 μm [7,8] and effectively separates the wear couple, although it can be broken under increased pressure or temperature conditions. Unfortunately, it usually also absorbs very hard worn out fragments of the reinforcement, leading to increased grooving and wear. Therefore, it is difficult to evaluate the relatively differentiated values of friction coefficients for hybrid composites [3,9]. Generally, graphite reduces the friction coefficient, which in the case of matrix alloy Al-2%Si with 4% C/12% Al_2O_3 composite material falls to about 0.4 [4].

Apart from these benefits, graphite can deteriorate strength properties. As M.L.T. Guo and C.Y.A. Tsao say [7] the amount of graphite flakes up to 5% promoted fracture-toughness effect and content of over 8% of graphite promoted the formation of solid lubricant. In another investigations [10] 2-5% content of graphite permitted to produce the lubricant film which did not weaken composite material and with content of 10-15% of graphite the friction coefficient was significantly reduced.

Similar role as graphite, iron oxides from abraded counterpart can perform. Flowing plastically and mixing with debris they prevent from adhesive wear and seizure [5,6]. In the contrary hard Al oxides debris remove lubricant film but when are embedded in the metal alloy matrix they harden the surface.

Generally different wear mechanisms depend on the wear condition: temperature, velocity of friction and load . In [6] with increasing load in Al-based composite materials reinforced with SiC particles first oxidation wear occurred, then delamination wear and under high load the adhesive wear. Hybrid composite material Al/Al_2O_3/C [9] at low friction velocity is ploughed and grooved but at high velocity with the rise of temperature melting of matrix material at the wear surface may occur.

In presented investigations composite materials based on 2024 and 7075 aluminium alloys were worn against grey iron counterparts under different loads. To determine the wear mechanism the microstructure of friction surfaces were analysed and discussed together with results of wear rate. The improvement was achieved by producing hybrid composite materials reinforced simultaneously with alumina and graphite fibres.

2. Experimental procedure

Production of composite materials consisted of two main stages: formation of a performs and their further infiltration with aluminium alloy by direct squeeze casting method. The 2024 and 7075 based aluminium alloy composite materials at as cast conditions were examined. Ceramic porous preforms were made of Saffil Al_2O_3 (96-97% Al_2O_3 z 3-4% SiO_2) fibres and part of them with graphite fibres delivered by SGL Carbon Ltd. Mixture of fibres in aqueous solution of the inorganic binder was drained off and formed to rectangular preforms of 60 × 40 × 10 mm. To create strong, chemically stable joints between fibres preforms were fired at 950°C and porous structure of preform composed from Al_2O_3 fibres is shown at Fig.1. Preforms preheated to the temperature of 500°C were placed in the cast mould and immediately the molten aluminium alloy was poured in order to infiltrate the porous ceramic preform. For all specimens, the same infiltration pressure of 75 MPa was applied and kept for 10 to 15 s until solidification was complete. Prepared composite materials contained 7 to 20% of Saffil Al_2O_3 fibres and 3 and 5% of graphite fibres. Microstructure of composite materials on 7075 matrix in planar random orientation of fibres is shown at Fig. 2.

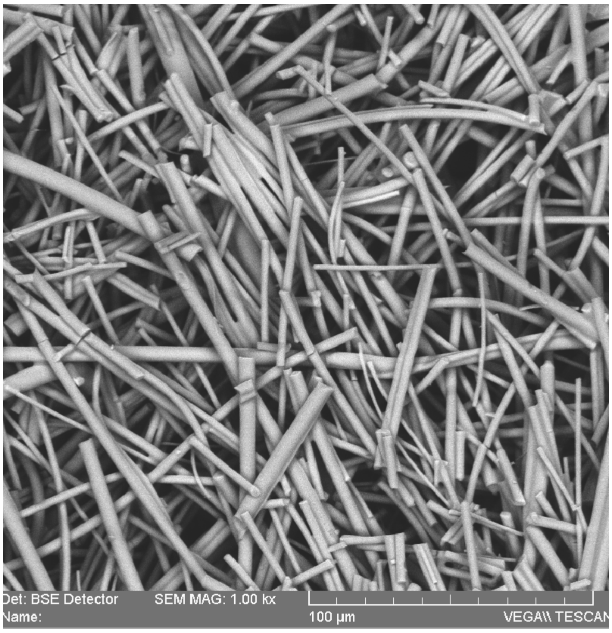

Fig. 1. Preform produced from the blended Saffil Al_2O_3 and graphite fibres

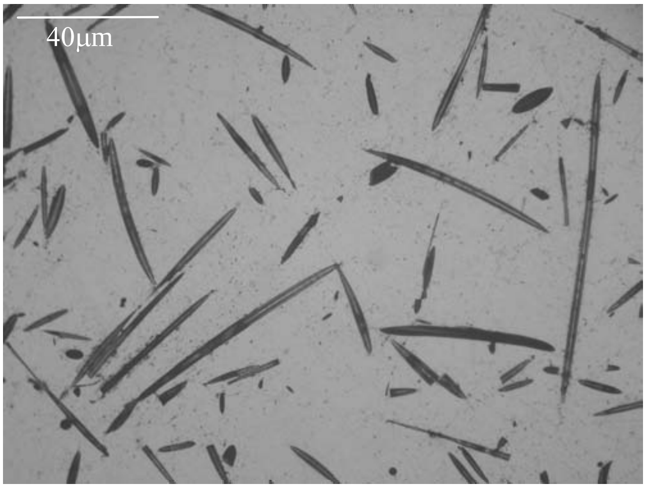

Fig. 2. Microstructure of the composite 7075+10 vol. %Al_2O_3 in surface with planar random orientation of fibres

Cylindrical specimens of 8 mm diameter were examined on pin-on-disc device. They were pressed to the nodular cast iron counterparts with forces corresponding to pressures of 0.8, 1.2 and 1.5 MPa. The counterpart discs rotated with average circumferential velocity of 1 m/s. Chemical quantitative depth profiling of counterparts after wear test was performed applying the glow discharge atomic emission spectrometer GDS 750 QDP LECO.

3. Discussion of results

3.1. Wear rate of the unreinforced matrix alloys and composite materials

Composite materials reinforced with 10 vol.% of Al_2O_3 fibres (7075-10% L) were worn only slightly faster than 7075 unreinforced alloy, especially under the lowest load 0.8 MPa, (see Fig. 3). Increase of SAFFIL fibre content in the 7075 matrix to 20% clearly reduced wear resistance, possibly as a result of debris from fragmented fibres which were transferred between rubbed couple. As a matter of fact wearing of specimens proceeded against counterpart with rubbed in its surface hard alumina particles. Specimens with planar random orientation to the friction surface (7075-20% II) showed the lowest resistance under high pressure of 1.5 MPa.

Similarly as presented in [11] composite materials made of aluminium alloy A356/ Al_2O_3 with normal orientation of alumina fibres to the wear surface showed less fibre fragmentation at the worn surface and were better resisted to wear than that with planar random orientation. As concluded, it resulted from spalling of whole fibres from the wear surface of the specimens with planar orientation, what caused intensive volume loss.

Reinforcing of relatively softer 2024 matrix with 10 vol.% of SAFFIL fibres improved wear resistance only under load of 1.5 MPa. Whereas under small load unreinforced 2024 alloy was more resistant unlike than in the case of 7075 based materials where composite materials under all applied loads worn faster. It could be found, that only reinforcing of strongly loaded and relatively soft alloys will be reasonable.

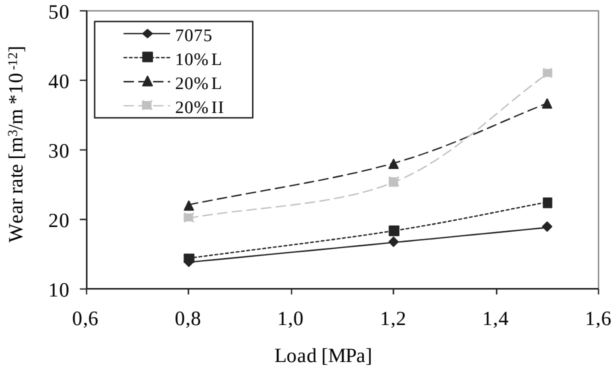

Fig. 3. Effect of load and orientation of Saffil Al_2O_3 fibres on wear of 7075 unreinforced matrix and composite materials with 10% and 20 vol. % of Al_2O_3 fibres

In the case of 2024 Al-based composite materials containing Saffil fibres under pressure of 0.8 MPa the wear resistance was worse than of the 2024 unreinforced matrix, but under higher load was better than of the matrix (see Fig. 4). Ceramic reinforcement caused significant increase of friction coefficient (see Fig. 5), similarly in 7075 based composite materials with normal oriented fibres. Slightly smaller coefficient in relation to the matrix was observed at planar random orientation of fibres for 7075 Al based composite materials (Fig. 6).

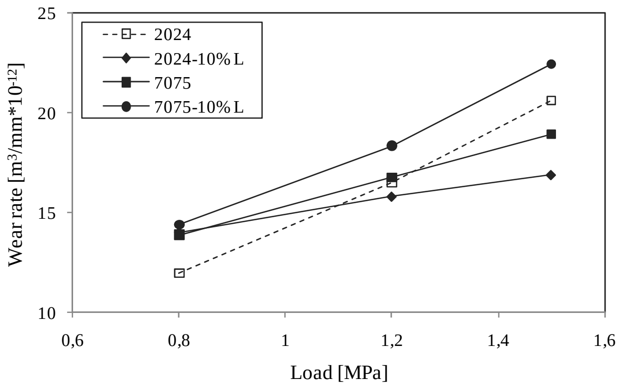

Fig. 4. Effect of load and orientation of Al_2O_3 Saffil fibres on wear of 2024 and 7075 matrix alloys and composite materials on their bases

Investigations of the 7075 based composite materials containing 10 vol.% of Al_2O_3 Saffil fibres and 3% of graphite fibres, especially under high load, revealed the improvement of wear resistance. Increase of pressure from 1.2 to 1.5 MPa caused only slight increase of wear rate to 15 [m^3/m 10^{-12}] for 7075-10%+3% C II composite material, whereas the wear for composite material without graphite fibres (10% L) was larger and its value was 22.5 [$m^3/m\ 10^{-12}$]. Concluding, the composite materials containing 3% of graphite exhibited about 30% better resistance than unreinforced 7075 alloy.

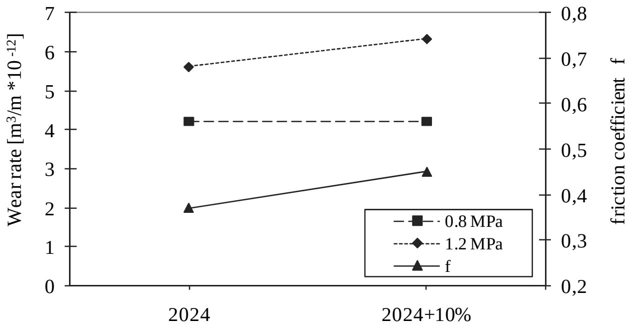

Fig. 5. Wear rate and friction coefficient of the unreinforced matrix 2024 and 2024 Al based composite material reinforced with 10 vol.% Al_2O_3 Saffil fibres after T6 examined under pressures of 0.8 and 1.2 MPa

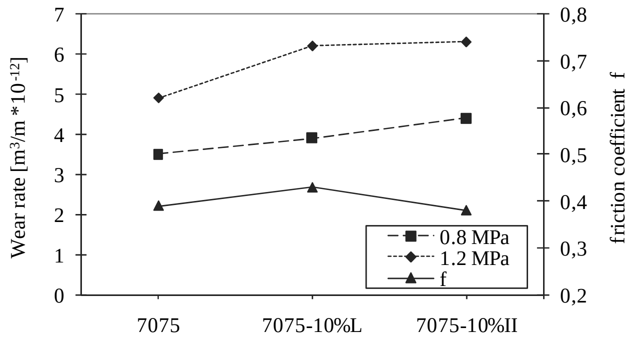

Fig. 6. Wear rate and friction coefficient and of the matrix 7075 and composite reinforced with 10% vol. Al_2O_3 after T6 examined under pressures of 0.8 and 1.2 MPa

3.2. Microstructure of wear surface. Wear mechanisms

In order to determine wear mechanism, in respect to applied load and fibre orientation microscopic observations of wear surface were performed. At Fig. 7 wear surfaces of unreinforced specimens and composite materials after test under pressure of 0.8 MPa are shown. It could be found, that surface of unreinforced alloy remained in good conditions even after test applying the relatively high pressure of 0.8 MPa. Grooving and deformation of microcontacts with slight erosion was mainly observed. Oxide layers formed on the surface protected counterpart against adhesion and welding. 7075 alloy in relation to 2024 revealed higher susceptibility to pits formation which subsequently were deepened and wedged by debris.

Wear mechanism can change when test conditions are more severe. As it was found in [12] higher friction velocity of 4 m/s caused melting and adhesive wearing phenomena in 7075 alloy. Also cast (without pressure) not strengthened alloys, what was observed in presented investigation exhibited higher wear rate, probably resulting from higher volume content of microporosities and coarser grains.

The surface of 2024 Al based composite materials (see Fig. 7b), slightly differs from unreinforced surface alloy. It is found more smooth wear surface of composite material with the tendency for closing arising pinholes by plastic deformations of subsurface. Intensively worn surface of 7075 based composite material was observed with the numerous, though small pinholes what indicates that the specimen was strongly worn even deep under surface (see Fig. 7d).

More informations on wear mechanism brought observations of the subsurface microstructure. At the Figure 8a cross-section of surface of unreinforced specimen made of 2024 Al alloy after wear test under pressure of 1.5 MPa is presented. It could be seen slightly deformed dendritic structure of alloy close to the friction surface and materials in the form of particles from the friction surface, namely from the 2024 Al sample and counterpart were rubbed in the partly deformed crystals. Similar phenomenon was observed in unreinforced 7075 specimen worn under both pressures of 1.2 MPa and 1.5 MPa. Additionally in some places plastic flow of thin ca. 5μm layers occurred, which with time were detached from the base material, (see Fig. 8b). Generally, it could be concluded, that at the surface of unreinforced specimens protective layer from comminuted, plastically distorted and oxidized particles was formed. This hardened layer efficiently reduced wear rate and possible grooving and plastic deformation effected on the smoothness of the specimen surface.

After T6 treatment surface of unreinforced 2024 specimen worn under the pressure of 0.8 MPa was grooved and successively uncovered layers oxidized. Slight grooving and plastic flow took place with partly deformed surface grains. Increasing of the load to 1.2 MPa resulted in deeper deformation zone, (see Fig. 9a) and mixing and rubbing debris in specimen proceeded. Produced grooves were deepened possibly by exfoliated alumina layer from the matrix material and particles of iron compounds from the counterpart. Collected in the pinholes waste materials could be covered and subsequently closed by plastically deformed matrix alloy. With time, cracking and exfoliating of these thin layers proceeded.

The 7075 Al alloy is characterized by higher hardness than the 2024 Al alloy, thus exhibiting better resistance to plastic deformation of the sublayer. Under low pressure of 0.8 MPa this process is almost invisible. Grains, prior deformed are gradually abraded, (see Fig. 9b). With increase of pressure, only directly under formed grooves, strongly deformed microstructure could be observed. Generally heat treatment T6 almost did not affected on the wear mechanism of the matrix, partially deformed grains at the surface are gradually abraded.

Observations of composite subsurfaces evidenced, dependently on applied load and fibre fraction the abrasive wear or formation or mechanically mixed layer MML.

Under pressures of 0.8 MPa and 1.2 MPa superficial dendrite arms were slightly plastic deformed and segments of partly cracked fibres moved in accordance with direction friction forces. Under largest pressure of 1.5 MPa the depth of MML arose significantly to 20 μm layer, (see Fig. 10a) in which apparent waste materials and fragments of fibres were mixed. According to the concept established in [12] under this layer the plastic deformation zone should be formed. The main function of strengthening fibres is to restrain this process and join the MML with base material. Unfortunately premature cracking of brittle fibres and their transport in deformed subsurface was frequently observed.

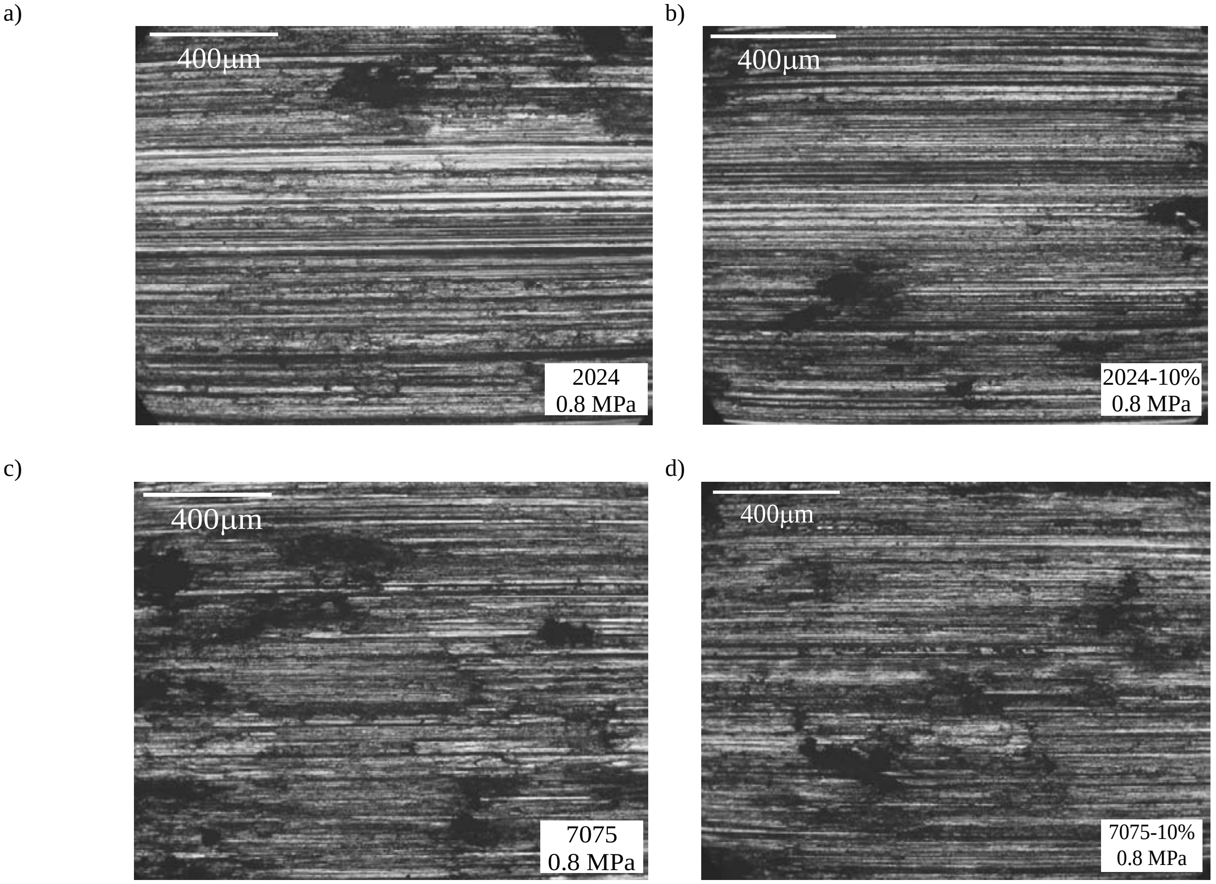

Fig. 7. The worn surfaces of specimens tested under pressure of 0.8 MPa. Unreinforced 2024 alloy (a) and unreinforced 7075 alloy (c), 2024 alloy based composite material reinforced with 10 vol. % of Al_2O_3 Saffil fibres (b), and 7075 based composite material reinforced with 10% of Al_2O_3 Saffil fibres (d)

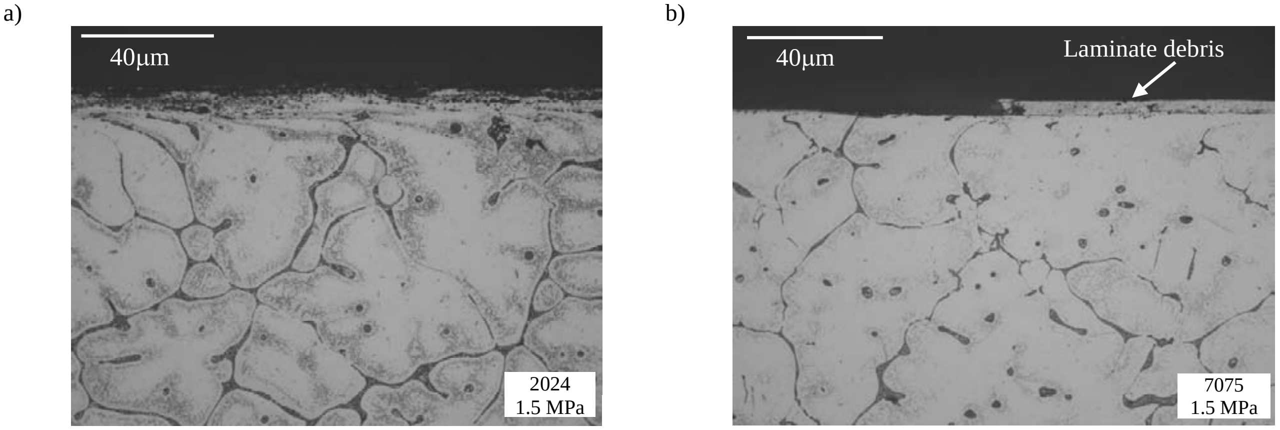

Fig. 8. Longitudinal cross-section of subsurfaces of unreinforced specimens of 2024 and 7075 worn under pressure of 1.5 MPa. Slightly deformed crystals with rubbed debris in 2024 specimen (a), compact delamination of 7075 specimen (b)

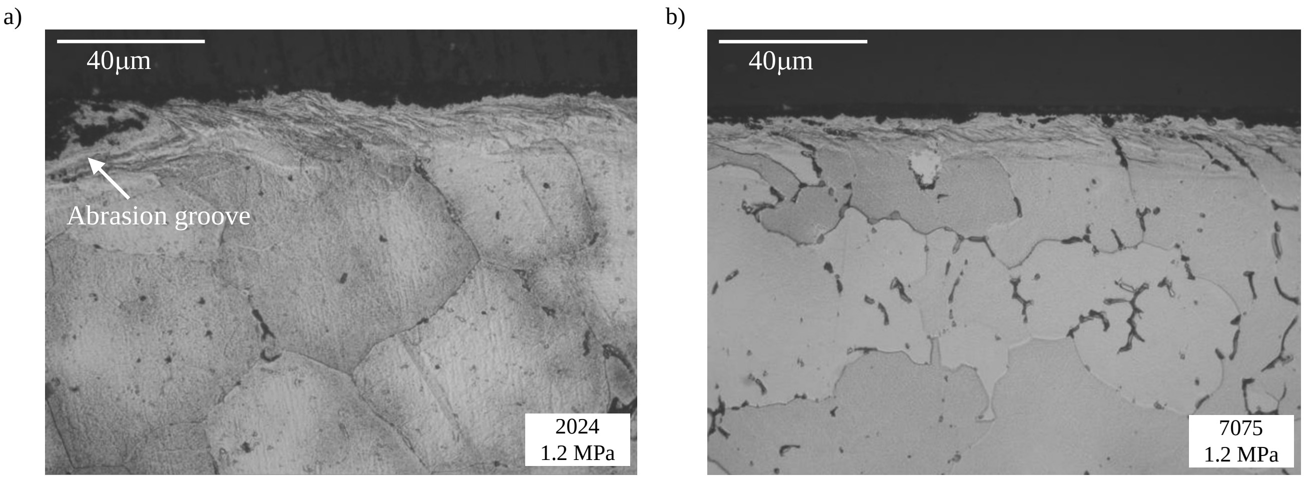

Fig. 9. Longitudinal cross-section of subsurfaces of unreinforced specimens of 2024 and 7075 alloys after T6 worn under pressure of 1.2 MPa

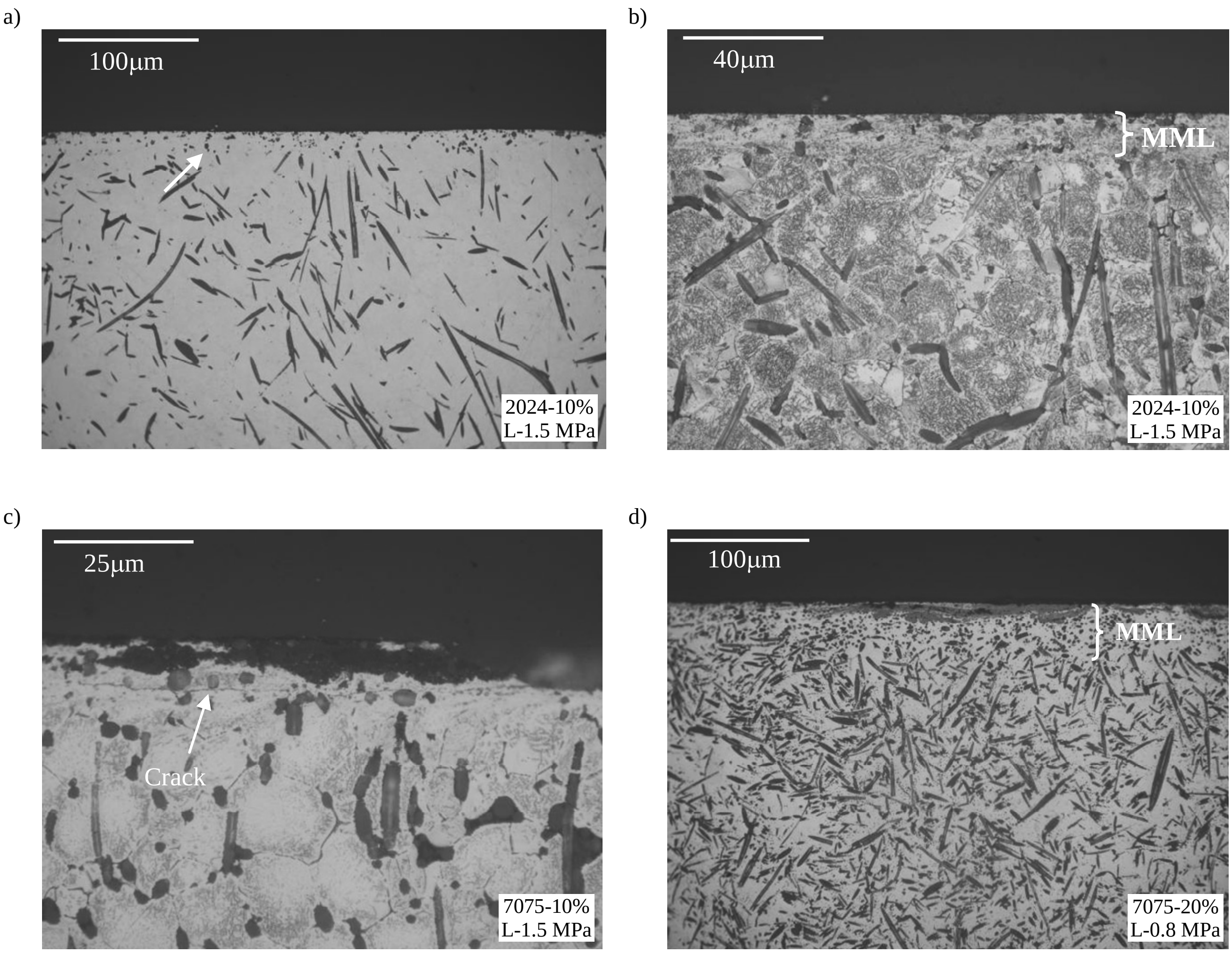

Fig. 10. Deformation in subsurfaces of 2024 and 7075 alloys based composite materials with Saffil fibres created under various loads

In the case of specimens containing 20 vol.% of Al_2O_3 L wear mechanism was different. Under small pressure of 0.8 MPa, the layer of 80μm thickness with small fragments of fibres was formed. Under strongly deformed layer at reinforcement-matrix interface large number of voids can arise. When concentration of voids diminishing transfer of stresses from the matrix to reinforcemens achieved critical value, than as it was determined in [13] (composites reinforced with SiC were examined) unstable shear stresses will be locally released under subsurfaces. This can led to crack initiation and delamination wear. Venkataraman and Sundararajan [14] founded, that MML is a main reason enhancing wear rate and the similar phenomena were observed in presented investigations. Under formed layer, where fragmented fibres were found, the abrupt wear increased resulting from the crack development and detaching of layer, (see indicated microcrack at Fig. 10c).

With increase of the pressure in the friction couple the layer was only slightly developed or removed completely. Possibly large number of hard fibre fragments were rubbed into counterface and thus some kind of abrader tool was created. This is evidenced by chemical analysis of counterpart surface showing increased Al content originated from alumina fibres, (see Fig. 11). Process of transferring of alumina fibres from the matrix to the counterpart was hindered by graphite lubricant film, limiting sticking of hard particles from alumina fibres to the counterface. Moreover transported mixture of waste materials with graphite and alumina particles prevented from welding of the counterpart to aluminium matrix. Thus 3% of graphite with higher 13% content of alumina fibres resulted in the lowest Al concentration in the counterpart and could be the way for elimination of seizure.

Finally, it could be proved that small amount of strengthening fibres is not sufficient to restrain plastic deformation and under high pressures and causes structure defects and delamination of MML, unlike in unreinforced specimens where slow wear occurred and delamintion was not observed.

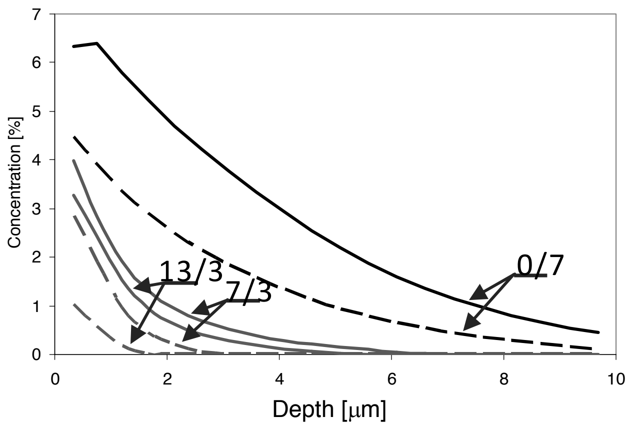

Fig. 11. Depth profiling showing Al concentration in counterparts surface after wear test against composite containing 7% of Al_2O_3 fibres (0/7), reinforced with 7% of Al_2O_3 and 3% of graphite (7/3), and reinforced with 13% of Al_2O_3 and 3% of graphite (13/3). Continuous line represents maximum, broken line minimum concentration of Al

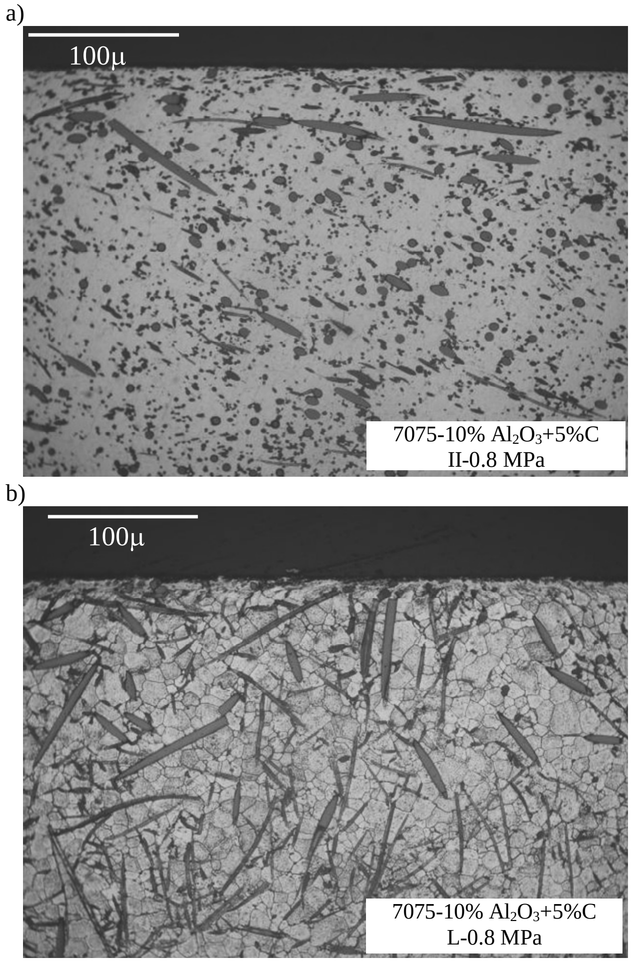

Fig. 12. Wear surface of 7075+10 vol. % Al_2O_3+5%C specimen with normal (a) and planar random orientation of fibres to friction surface (b) after test performed under pressure of 0.8 MPa

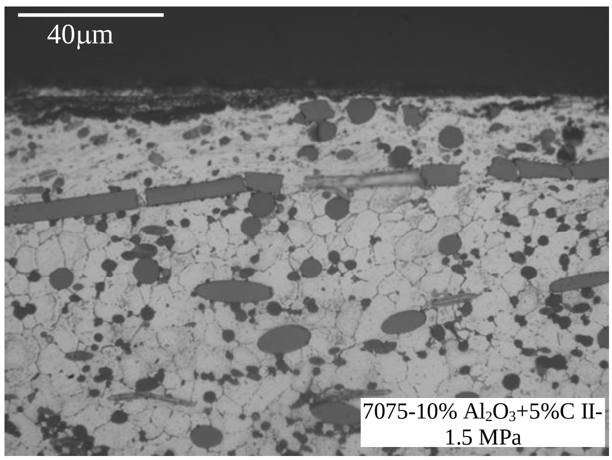

Fig. 13. Wear surface of 7075+10% Al_2O_3 Saffil+5%C specimen with planar random orientation of fibres to friction surface

Applying graphite fibres for reinforcing composite materials resulted in strengthening of subsurface as well as in the small plastic deformation and thermal conductivity. At small pressure of 0.8 MPa, fibres were almost intact and efficiently restrained deformation, (see Fig. 12a). Ends of normal fibre orientated under wear surface were broken and aluminium alloy grains were slightly deformed, (see Fig. 12b).

High pressure of 1.5 MPa caused distinct grains deformation, with transport of fragmented graphite fibres, (see Fig. 13). As the wear process proceeded uncovering new graphite segments they were acting as the pockets of lubricant. Process with planar random orientation of fibres was similar. Fibres restrained matrix plastic deformation, though under formed grooves of wear surface debris conglomerates with high pressure caused strong deformation and flowing of aluminium matrix.

4. Conclusions

Dry sliding wear behavior of aluminium based composite materials reinforced with Al_2O_3 Saffil and graphite fibres against nodular grey iron were examined by pin-on-disc method under different loads. Results can be summarized as follows:

1. Wear resistance of 2024 or 7075 aluminum based composite materials reinforced with Al_2O_3 fibres decreases with increase of fibre content.
2. Transferred and embedded into couterpart fractured segments of fibres intensely abrade composite specimens.
3. Under lower load composite specimens were worn slowly and mechanically mixed layer MML was formed.
4. Fibres normal oriented to the friction surface transferring loads deep into matrix material caused higher deformation of the matrix.
5. Introduced graphite fibres strengthen the subsurface and improve wear resistance of the composite materials.

Acknowledgements

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