

Jerzy MYALSKI*, Andrzej POSMYK**, Bartosz HEKNER***, Marcin GODZIERZ****

THE INFLUENCE OF GLASSY CARBON AND ITS FORMS ON TRIBOLOGICAL PROPERTIES OF ALUMINIUM MATRIX COMPOSITES

WPLYW WĘGLA SZKLISTEGO I JEGO POSTACI NA WŁAŚCIWOŚCI TRIBOLOGICZNE KOMPOZYTÓW Z OSNOWĄ ALUMINIOWĄ

Key words:

metal matrix composites, glassy carbon, wear, coefficient of friction, wear mechanisms.

Abstract

Carbon with an amorphous structure was used as a component to modify the tribological properties of engineering plastics. Its construction allows the formation of carbon-based wear products during friction, adhesively bonded to the surface of cooperating machine parts, acting as a solid lubricant. The work compares the tribological properties of two groups of composites with an aluminium alloy matrix in which glassy carbon appeared in the form of particles and an open cell foam fulfilling the role of strengthening the matrix. The use of spatial structures of reinforcement provides, in comparison with the strengthening of particles, homogeneity of carbon distribution in the entire volume of the composite. The tests carried out on a pin-disc tester showed that the use of spatial carbon structures in the composite ensures a greater coefficient of friction stability than when reinforcing with particles, and the coefficient of friction with a small proportion of carbon foams (about 1 wt%) is comparable with the coefficient of friction in the contact with composites containing 5-10% carbon particles in granular form.

Słowa kluczowe:

kompozyty z osnową metalową, węgiel szklisty, zużycie, współczynnik tarcia, mechanizmy zużycia.

Streszczenie

Węgiel o strukturze amorficznej został wykorzystywany jako komponent do modyfikacji właściwości tribologicznych tworzyw konstrukcyjnych. Jego budowa pozwala na tworzenie się w trakcie tarcia węglowych produktów zużycia, połączonych adhezyjnie z powierzchnią współpracujących części maszyn, pełniących funkcję smaru stałego. W pracy porównano właściwości tribologiczne dwóch grup kompozytów z osnową ze stopu aluminium, w których węgiel szklisty występował w postaci cząstek oraz piany otwartokomórkowej pełniącej rolę umocnienia osnowy. Wykorzystanie przestrzennych struktur zbrojenia zapewnia, w porównaniu z umocnieniem cząstkami, homogeniczność rozkładu węgla w całej objętości kompozytu. Przeprowadzone badania na testerze pin-disc wykazały, że wykorzystanie w kompozycie przestrzennych struktur węglowych zapewnia większą stabilność współczynnika tarcia niż przy umocnieniu cząstkami, a współczynnik tarcia przy niewielkim udziale pian węglowych (około 1% cz. wag.) jest porównywalny ze współczynnikiem tarcia w skojarzeniu z kompozytami zawierającymi 5–10% cząstek węglowych w postaci ziarnistej.

* ORCID: 0000-0003-0646-7624. Silesian University of Technology, Faculty of Materials Engineering and Metallurgy, Krasińskiego 8 Street, 40-019 Katowice, Poland

** ORCID: 0000-0003-2943-2379. Silesian University of Technology, Faculty of Transport, Krasińskiego 8 Street, 40-019 Katowice, Poland

*** ORCID: 0000-0003-4151-1395. Silesian University of Technology, Faculty of Materials Engineering and Metallurgy, Krasińskiego 8 Street, 40-019 Katowice, Poland

**** ORCID: 0000-0001-9351-7452. Silesian University of Technology, Faculty of Materials Engineering and Metallurgy, Krasińskiego 8 Street, 40-019 Katowice, Poland

INTRODUCTION

The increased demand for durable, low-density materials for aviation and aeronautics, and now also for the automotive industry, has led to the development and use of composites with a metal matrix (MMC). Composite materials based on Al and Mg alloys are increasingly replacing light metal alloys that do not meet the requirements set for them. The skilful combination of different groups of materials in the composite allows synergistic interaction ensuring the elimination of unfavourable features of the materials forming the composite, while maintaining the desired features. By introducing hard ceramic materials into the aluminium alloy, it is possible to obtain a composite that will have good physicochemical properties (low density, high electrical and thermal conductivity, and chemical resistance) and good strength properties (high modulus of elasticity, strength, stiffness, hardness, and low deformability and thermal expansion), as well as good tribological properties (wear resistance, and the coefficient of friction) [L. 1, 2]. It is possible not only to choose the chemical composition of the reinforcement material, but also its stereological features (volume fraction, dimensions, and form, e.g., particles, whiskers, and fibres, and their positions relative to the friction surface). The use of this type of composites also resulted from its low manufacturing costs, as well as the ability to form finished products using conventional metal forming processes such as rolling, forging, and extrusion [L. 3, 4].

Homogeneous composites (containing one type of particles) reinforced with SiC, Al₂O₃, TiC, Si₃N₄C, and ZrO₂ particles contributed to the creation of a new generation of heterophasic composites [L. 5, 6]. In these types of composites, two types of reinforcing phase material are used. Most often, they are "hard" particles resistant to wear and "soft" particles, such as mica, graphite, and MoS₂, reducing the coefficient of friction and limiting the wear of parts cooperating with the composite part [L. 7, 8].

An alternative solution for this type of heterophasic composites may be the use of only one type of reinforcing phase, characterized by high hardness and resistance to wear and also acting as a solid lubricant. Such a material may be amorphous carbon (glassy carbon – GC) [L. 9, 10]. The use of glassy carbon in metal composites developed at the Silesian University of Technology has been confirmed in many publications [L. 11–15]. The production of composites reinforced with glassy carbon particles causes many technological difficulties. This is due to the low density of the carbonaceous material and its poor wettability by the liquid matrix metal. Voids and pores at the interface boundary, uneven particle distribution, agglomeration, or sedimentation in the matrix appear in composites. The use of reinforcing

spatial structures of glassy carbon in the form of foam can prevent uneven distribution [L. 17, 18].

The article compares the effect of the form of the strengthening component, which are the particles and open-celled foams of glassy carbon, on the tribological properties of aluminium matrix composites.

RESEARCH MATERIAL AND METHODS

The glassy carbon in the form of particles and foam used for the research was produced in a high temperature pyrolysis process of polymer precursors. The precursor to the glassy carbon particles was a phenol-formaldehyde resin. In contrast, the carbon foams were obtained using polyurethane foam as the skeleton, which was covered with a phenolic resin to preserve the porous, initial structure. The particles and the resin foam preform were pyrolysed at the temperature of 1000°C, under vacuum conditions, at a precisely determined heating rate [L. 19]. The composite matrix was technically pure aluminium. The composites were produced by pressure-vacuum infiltration on a Degussa press at 720°C and a pressing pressure of 10 MPa. Two groups of composites were used in the research – those strengthened with particles containing 2.5, 5, 7.5 and 10 wt% particles and composites reinforced with glassy carbon foams of varying porosity (Fig. 1).

In the foam-strengthened composites, the different amount of reinforcement was the result of the initial porosity of the polyurethane foam determined by the PPI index, which defines the number of foam cells per length of 1 inch. Foams with porosities of 20, 40, 60, and 80 PPI were used in the research. This resulted in a slight change in the amount of glassy carbon in the composite, which was for foams with the porosity of 20 PPI – 0.7 wt%, 35 PPI – 1.1%, 60 PPI 1.3 wt%, and 80 PPI 1.7 wt%. In Figure 1, it can be seen that the foam has a continuous skeleton structure, consisting of neighbouring cells (spheres) in which windows appear. The thickness of the cell and window walls varies depending on the PPI value, and this affects a small change in the contribution of reinforcement to the composite.

The coefficient of friction tests were carried out on a T-01M tribological tester, in the pin-disc system, in technically dry friction, 10 N load, sliding velocity of 1 m/s, and on friction paths of 1000 and 2500 m. The 6 mm diameter pin was made of GJL-350 grey cast iron. The results of changes in the coefficient of friction and wear are shown in Figs. 2 and 5.

In order to register changes occurring on the friction surface, microstructure analysis was performed using a Hitachi 3400N scanning microscope with an analysis of the chemical composite by the EDS method and surface topography analysis using a MICRO PROF FRT optical profilometer.

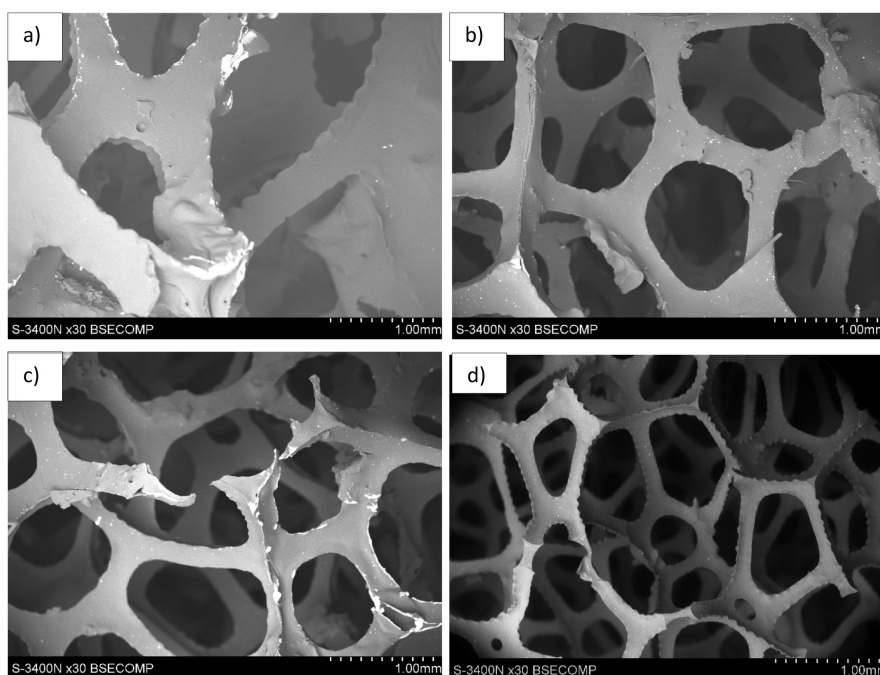


Fig. 1. Structure of used as reinforcing phase carbon foams with porosity of 30 PPI (a), 40 PPI (b), 60 PPI (c), 80 PPI (d)

Rys. 1. Struktura stosowanych jako umocnienie pianek węglowych o porowatości 20 PPI (a), 40 PPI (b), 60 PPI (c), 80 PPI (d)

RESULTS

The results of the tribological tests showed that the proportion and the form of reinforcement used influence the coefficient of friction value. In the particle-strengthened composites, the influence of the GC share on the coefficient of friction value can be noticed only in the initial stage of friction and changes to 0.7 for a share of 2.5% GC to 0.46 for a 7.5% share. After a longer time

of friction, the coefficient of friction values, regardless of the particle content, are similar to each other. The increase in the proportion of particles in the composite contributes to shortening the run-in time and the course of momentary changes in the coefficient of friction. The smaller the share, the longer are the run-in paths and the greater is the instability of changes in the coefficient of friction (**Fig. 2**). The friction coefficient of the Al + 2.5% GC composite stabilized only after 900 m of

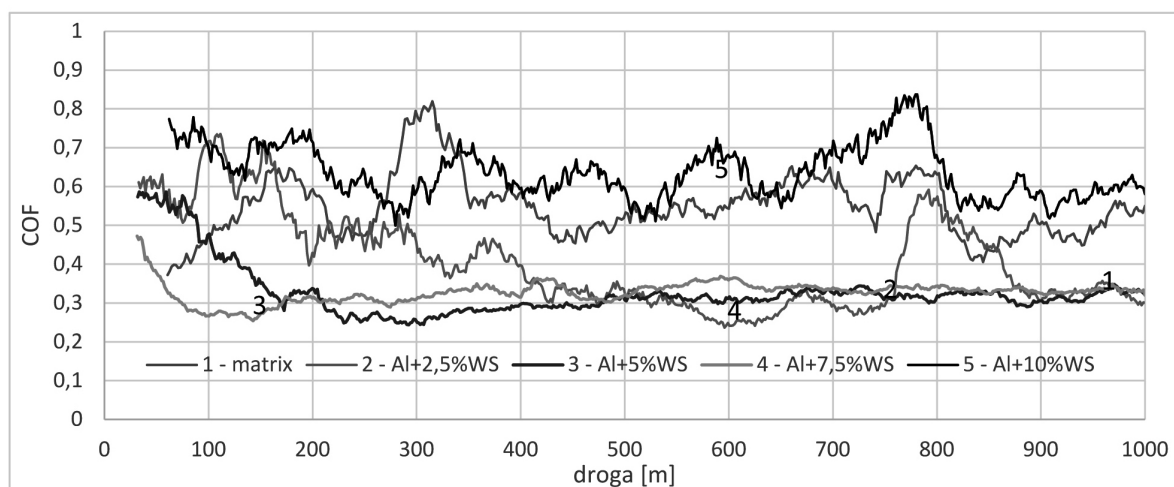


Fig. 2. Friction coefficient vs. glassy carbon content in composite: 1 – matrix, 2 2.5% GC, 3 – 5% GC, 4 – 7.5% GC, and 5–10% GC

Rys. 2. Zależność współczynnika tarcia od ilości węgla szklatego w kompozycie: 1 – Al, 2 – 2,5% WS, 3 – 5% WS, 4 – 7,5% WS, 5 – 10% WS

the friction path. A completely different characteristic of changes in the coefficient of friction was found in the composite with high particle density (Al + 10% GC). During the tests, the coefficient of friction value underwent rapid changes, similar to the coefficient of friction in the matrix material. The analysis of the

friction surface of the composites and the matrix allowed the causes that influence the coefficient of friction to be determined (**Fig. 3**). It can be observed that the matrix is worn by micro-scraping, furrowing, and plastic deformation of small areas as well as adhesive plating of the matrix with wear products.

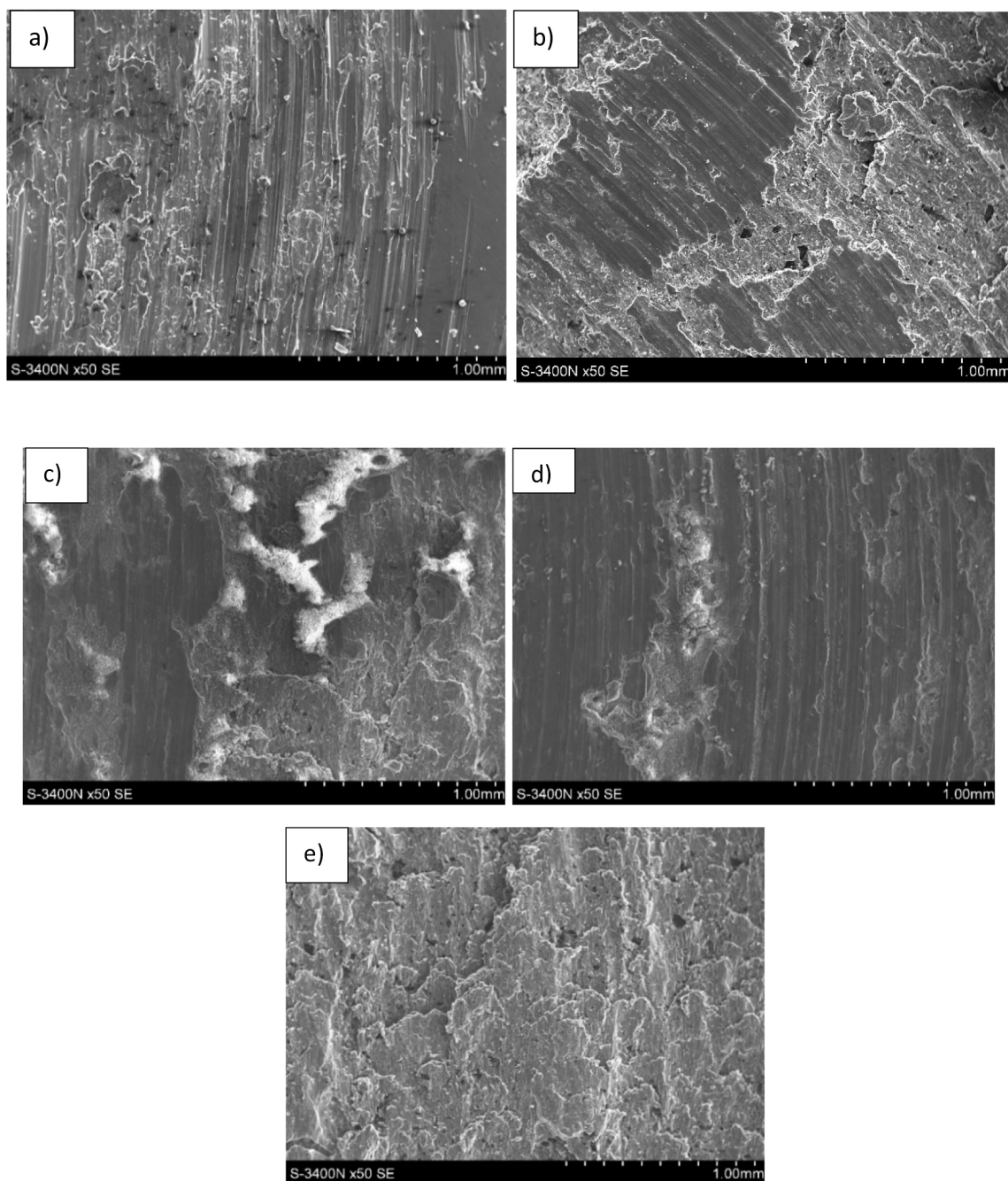


Fig. 3. Surface topography of matrix (a) and composite with reinforcing glassy carbon particle of 2.5% vol. (b), 5% vol. (c), 7.5% vol. (d), and 10% vol. (e)

Rys. 3. Topografia powierzchni osnowy (a) i kompozytów umacnianych: z dodatkiem 2,5% obj. (b), 5% obj. (c), 7,5% obj. (d) oraz 10 % obj. (e) cząstek węgla szklanego, SEM

The addition of glassy carbon causes the micro-dissection process to occur primarily in the glassy carbon particles. Wear products adhesively bonded to the composite matrix (**Figs. 3c, d**), and detached matrix fragments (**Fig. 3b**) appear around the particle. On the other hand, in the composite with the highest GC content, plastically deformed areas adhesively joined to the matrix without plastic deformation can be observed. Deformed areas are present on the entire friction surface of the composite. The lack of GC particles visible in the friction trace is the result of the overlap of the deformed layer on the surface of

the particles as well as their pulling-out and removal from the composite. The view of the topography of the friction surface can be a confirmation (**Fig. 4**). In the composite containing 2.5% GC, particles can be seen protruding from the friction surface and places where the particles were pulled out of the matrix. In the composite containing 10% GC, practically no reinforcing particles are seen, only depressions resulting from removal of the carbon particles from the composite. This contributes to a significant increase in the wear of the composite, even greater than the wear of the matrix material (**Fig. 5**).

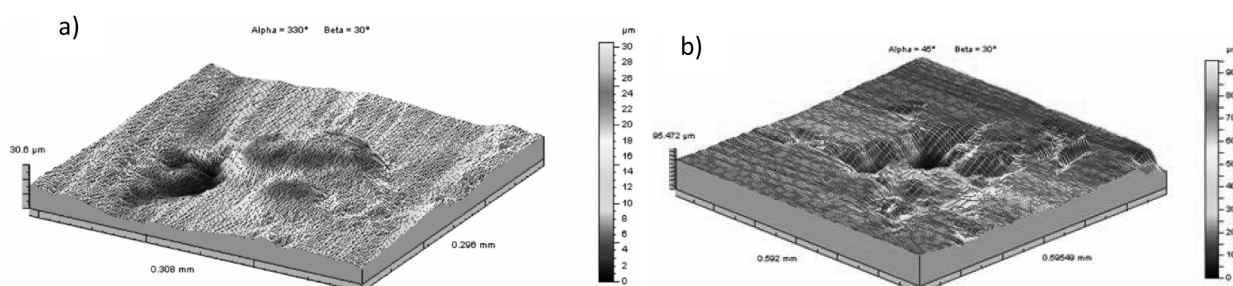


Fig. 4. Friction surface topography of composite including 2.5% GC (a) and 10% GC (b)

Rys. 4. Topografia powierzchni tarcia kompozytu zawierającego 2% WS (a) i 10% WS (b)

The carbon particles protruding above the friction surface determine the friction process. They bear the mechanical and thermal loads, and the resulting carbonaceous wear products are adhesively bonded to the composite surface layer or the material of the pin cooperating with it. This contributes to the creation of a lubricating film containing a solid lubricant, limiting the wear of both the composite and the material of the pin.

containing 2.5% GC, the presence of oxygen, iron, and carbon can be observed on the friction surface. Despite the small amount of carbon particles in the composite, an even distribution of carbon products can be observed over the entire friction surface. In the areas of plastically deformed fragments of the matrix material, the presence of cast iron pin wear products is observed, which cannot be seen in places from where fragments of the plastically deformed matrix layer were detached.

In the composite containing 10% glassy carbon, the particles are quickly removed from the friction surface, resulting in intense deformation of the matrix and the formation of plastic deformation layers. As a result, we are dealing with friction between the composite matrix and the cast iron pin. Therefore, the coefficients of friction of the matrix material and the composite with the high carbon content are similar. Large sized particles and those particles weakly connected with the matrix are torn out of the matrix. The stereological studies showed that, in the composites with the high content of reinforcement, their size is much larger than in the composites with a smaller content (**Fig. 7**). This is due to the technology of obtaining the composite. The composites reinforced with particles were obtained in two stages. In the first stage, the composite powder was produced, which in the second stage was pressed and sintered on a Degussa press ($p = 10 \text{ MPa}$, $T = 760^\circ\text{C}$).

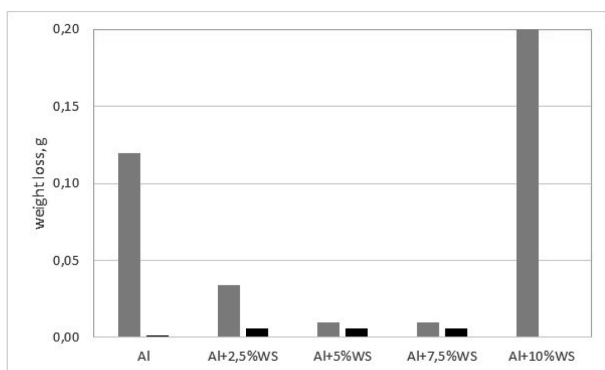


Fig. 5. Glassy carbon content vs. wear of composite with glassy carbon reinforcing particles

Rys. 5. Wpływ ilości węgla szklistego na zużycie kompozytów umacnianych cząstkami węglowymi

As shown in **Fig. 6**, showing the EDS analysis results of the friction surface of the composite

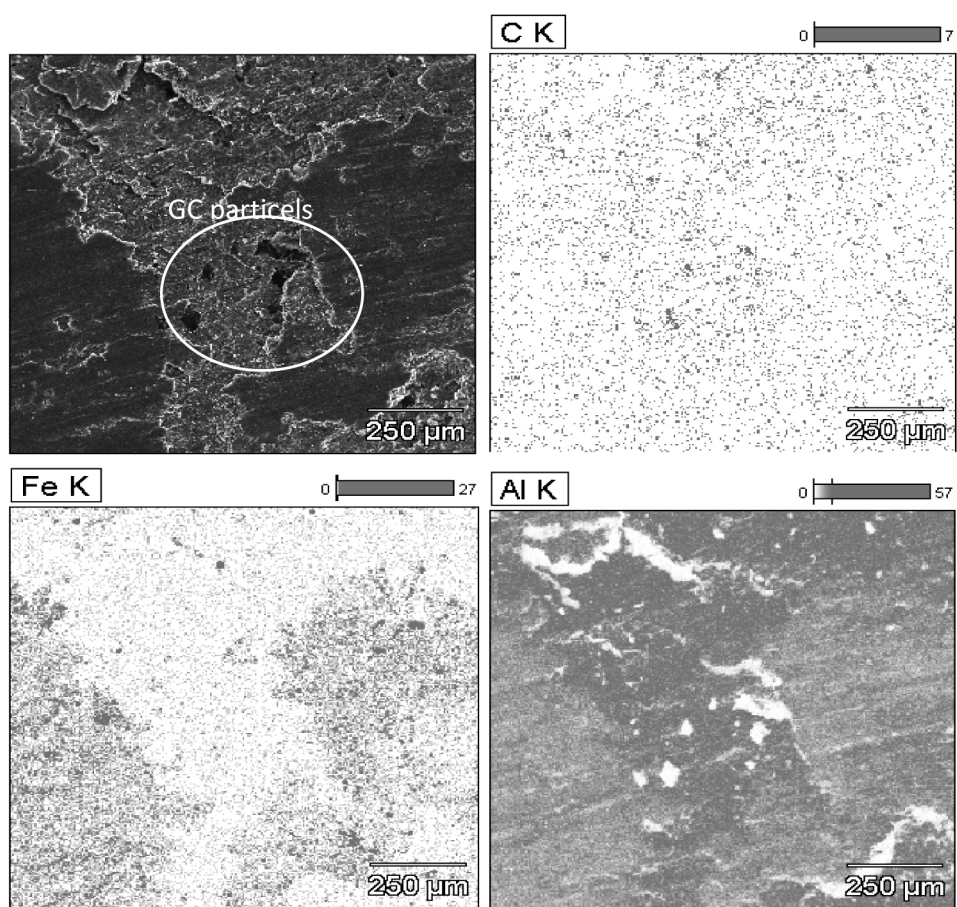


Fig. 6. Chemical analysis of surface topography of composite Al+2.5% GC, SEM, EDS
Rys. 6. Analiza składu chemicznego powierzchni tarcia kompozytu Al+2,5% WS SEM, EDS

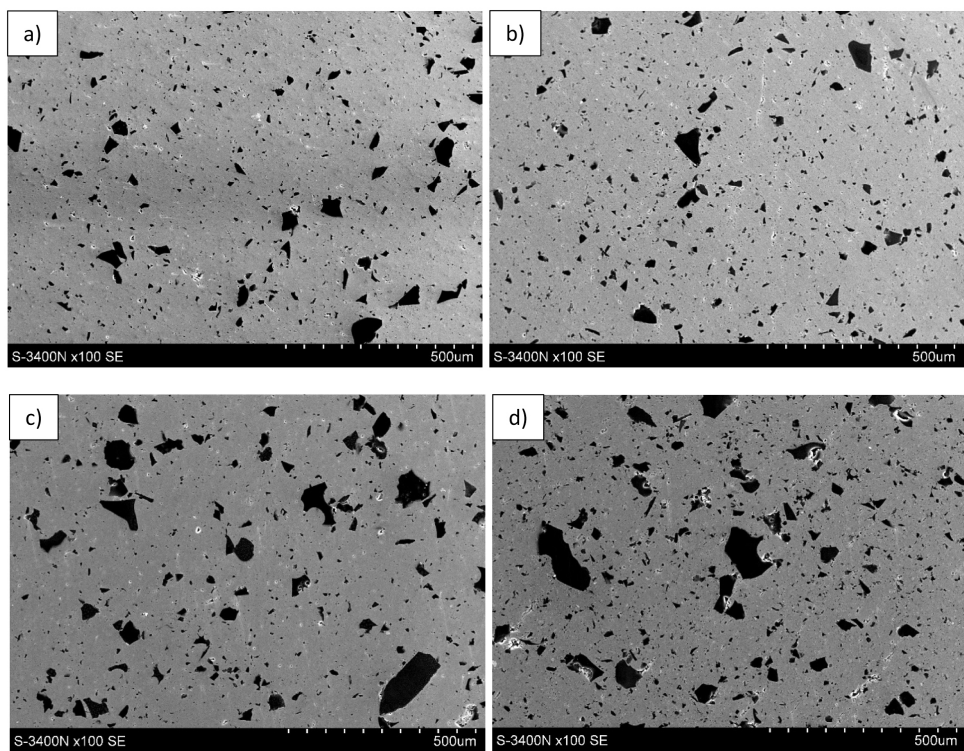


Fig. 7. Microstructure of composites containing 2.5% GC (a), 5% GC (b), 7.5% GC (c), and 10% GC (d)
Rys. 7. Mikrostruktura kompozytów zawierających 2,5% WS (a), 5% WS (b), 7,5% WS (c) i 10% WS (d)

In order to evenly distribute the glassy carbon in the matrix, the homogenization of the aluminium and glassy carbon powders was carried out in a rotary mill for 2 hours. During mixing, however, additional fragmentation of the initial glassy carbon particle size occurred (grains with 60–120 μm granulation were used in the study). During the homogenization of the composite powder, the large amount of glassy carbon hindered its fragmentation, which caused the size of the carbon particles to vary, depending on their contribution to the composite.

The average particle diameter determined in the stereological studies at the reinforcement amounts of 2.5, 5, 7.5, and 10% GC was, respectively, 42.9, 53.1, 78.2, and 121.7 μm , and the amount of large particles increased with an increasing share of reinforcement.

In the composites containing a small, the approximate content (about 1%) of carbon foam, the coefficient of friction value was determined primarily by the size of the cells in the foam. The smaller the diameter of the cell (higher PPI value), the lower was the coefficient of friction and its course was more stable (Fig. 8).

For the composites with porosities of 60 and 80 PPI, the coefficient of friction value did not change as a function of the friction path. Furthermore, the composite containing 40 PPI foam was characterized by a similar coefficient of friction, after a long cooperation path. Only for the composite reinforced with 20 PPI was the coefficient of friction about 0.5, which was close to the coefficient of friction of the matrix.

A similar value of the coefficient of friction was observed in the case of the composites reinforced with carbon particles at the content of 2.5%, in the initial stage of friction. This indicates that the distribution of carbon particles in the composite and the distance between neighbouring reinforcement particles are important. If the distances are large, at a small amount of reinforcement, the formation of an intermediate (carbon) layer on the surface of the composite occurs only after a longer period of cooperation. This is also the case with the strengthening by carbon foams. In foams containing large diameter cells (small PPI), there is no even distribution of carbon wear products on the surface of the composite or it requires a very long run-in stage (in the composite with 40 PPI foam, the coefficient of friction stabilizes after 1000 m), after which the coefficient the friction is about 0.5. The wear products of carbon foam with a smaller cell diameter (over 60 PPI) combine to evenly cover the matrix surface, reducing and stabilizing the coefficient of friction. This can be seen by analysing the friction trace surface of the composites reinforced with foams (Fig. 9).

In the composite containing foams with small cell diameters, plastic deformation of the matrix takes place around the carbon precipitates (in the centre of Fig. 9d), and the wear products are located at the interface between the components. In the foam composite with large cell diameters, one can observe furrowing, large plastic deformation of the matrix, and the detachment of plastically deformed matrix fragments. In Fig. 9b,

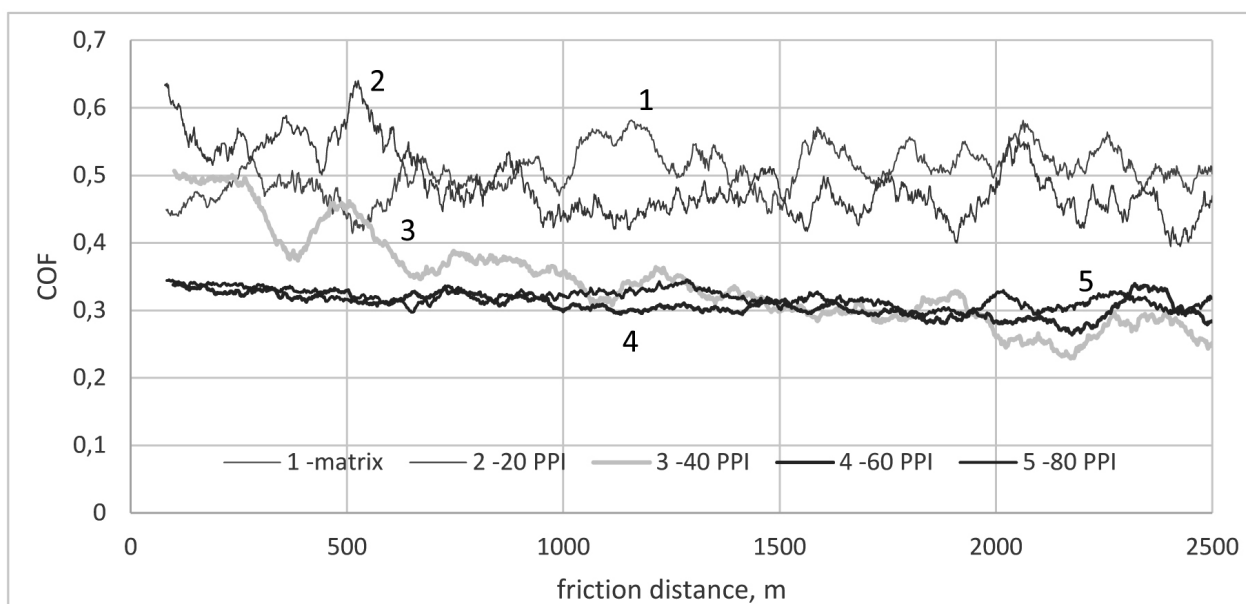


Fig. 8. Friction coefficient vs. sliding distance examined composites with carbon foams with different PPI levels: 1 – matrix, 2 – 30 PPI, 3 – 45 PPI, 4 – 60 PPI, and 5 – 80 PPI

Rys. 8. Zależność współczynnika tarcia od drogi badanych kompozytów z piankami węglowymi o różnej wartości PPI: 1 – matrix, 2 – 30 PPI, 3 – 45 PPI, 4 – 60 PPI, 5 – 80 PPI

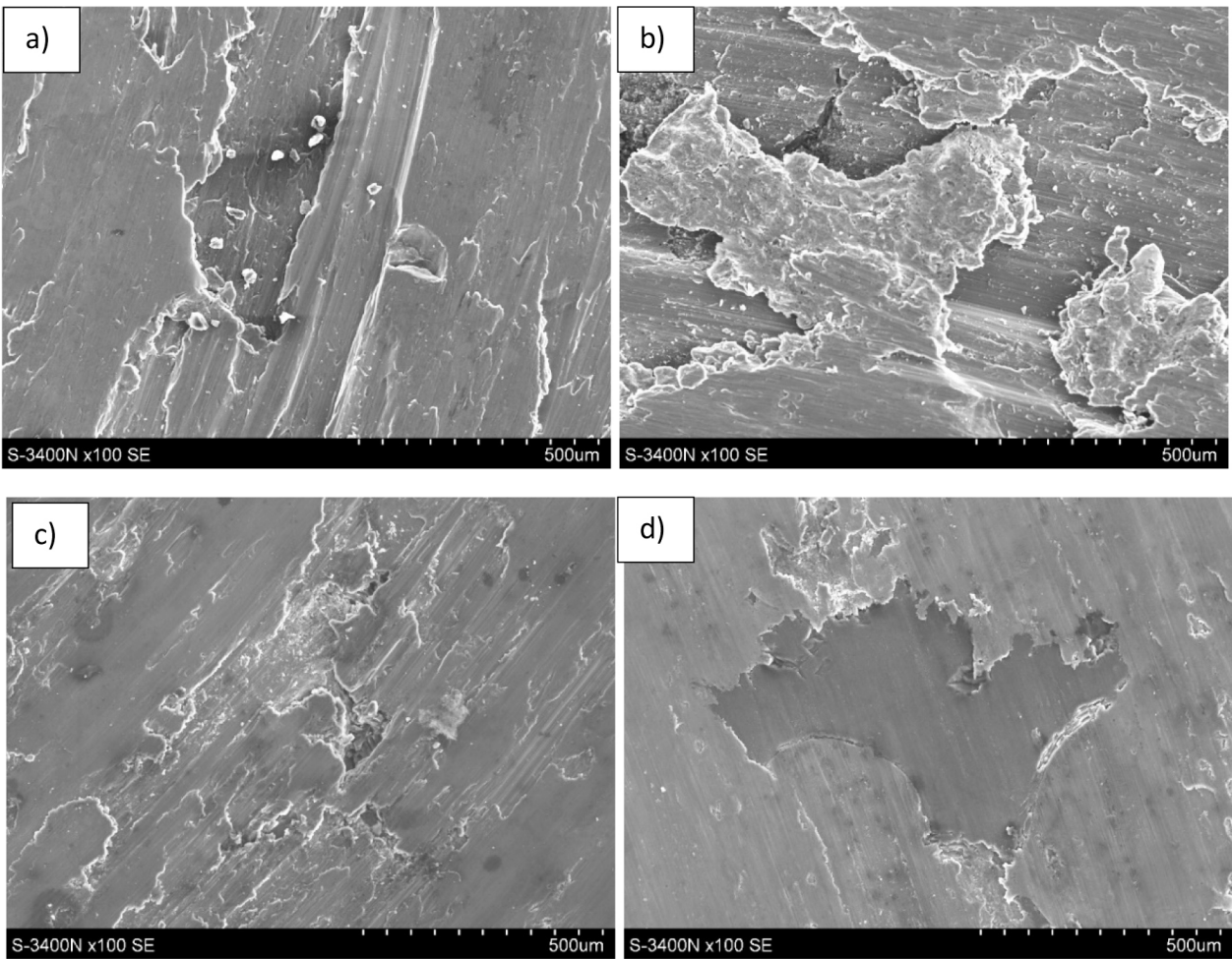


Fig. 9. Surface topography of composites with glassy carbon foam with porosity of 20 PPI (a), 40 PPI (b), 60 PPI (c), and 80 PPI (d), SEM

Rys. 9. Topografia powierzchni tarcia kompozytów z pianką węglową o porowatości 20 PPI (a), 40 PPI (b), 60 PPI (c) oraz 80 PPI (d), SEM

plating of wear products on the surface of the composite can be seen.

Adhesion is fostered by a small amount of carbon products on the friction surface. It also causes the instability of the coefficient of friction due to an increase in the friction force when removing wear products. The size of the foam cells also affects the wear of the composite (**Fig. 10**). The greatest wear occurred in the foam composite in which the cells had a diameter of about 0.8 mm (20 PPI) and a wall thickness of about 100 µm. In the composites with low porosity foams, a larger number of defects appear on the interface boundary, reducing the strength of the connection. The poor connection between the foam and the matrix can lead to pulling off large portions of the foam walls. The torn-off foam fragments are removed from the friction surface, and they do not foster the adhesion of carbon to the composite. In this case, there were similar wear mechanisms that were observed for the composites containing a large amount of reinforcement in which there were larger diameter particles.

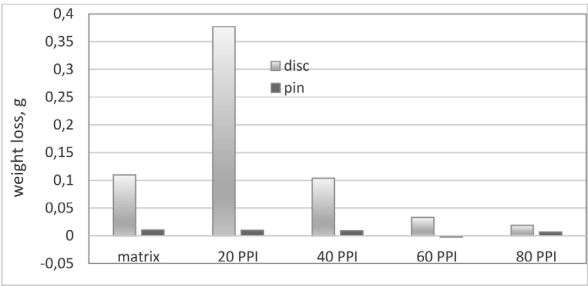


Fig. 10. Influence of PPI on wear of composite with foam reinforcing

Rys. 10. Wpływ wartości PPI na zużycie kompozytów umacnianych piankami

SUMMARY

The conducted research has shown that the form of reinforcement used may affect the tribological characteristics of the composite. The use of continuous

reinforcement in the composite contributes to an increase in the coefficient of friction and reduced wear. Already a small amount of carbon foam (~ 1% -40 PPI) allows one to reduce wear and achieve a coefficient of friction close to the value achieved with a large proportion (7.5%) of the same type of reinforcement, but in granular form. This is related to the properties of glassy carbon, which is characterized by high hardness, but low shear strength. As a result, small pieces of carbon deposited on the surface of the materials of the cooperating machine parts are separated during friction. The produced carbon film acts as a solid lubricant reducing the wear of the

composite and the material cooperating with it. Using reinforcement in the form of porous carbon foam contributes to very fast and even distribution of the carbon wear products on the friction surface and reduces the adhesive connection with the wear products of the matrix material.

ACKNOWLEDGMENT

The study is financially supported by NCN in the frame of the project UMO-016/23/N/ST8/00994.

REFERENCES

1. Prasad S.V., Asthana R.: Aluminum metal-matrix composites for automotive applications: tribological considerations, *Tribology Letters*, Vol. 17, No. 3, 2004, pp. 445–453.
2. Asif M., Chandra K., Misra P.S.: Development of Aluminium Based Hybrid Metal Matrix Composites for Heavy Duty Applications, *Journal of Minerals & Materials Characterization & Engineering*, Vol. 10, No. 14, 2011, pp. 1337–1344.
3. Kunze J.M., Bampton C.C.: Challenges to Developing and Producing MMCs for Space Applications, *Journal of Metal*, 2001, April, pp. 20–25.
4. Suresha S., Sridhara B.K.: Wear characteristics of hybrid aluminium matrix composites reinforced with graphite and silicon carbide particulates, *Composite Science and Technology*, 70, 2010, pp. 1652–1659.
5. Oluwatosin Bodunrin M., Kanayo Alaneme K., Heath Chown L.: Aluminium matrix hybrid composites: a review of reinforcement philosophies; mechanical, corrosion and tribological characteristics, *Journal of Materials Research and Technology*, v. 4, issue 4, 2015, pp. 434–445.
6. Umanath K., Palanikumar K., Selvamani S.T.: Analysis of dry sliding wear behaviour of Al6061/SiC/Al₂O₃ hybrid metal matrix composites, *Composites: Part B*, 56, 2014, pp. 472–476.
7. Baradeswaran A., Elaya Perumal A.: Wear and mechanical characteristics of Al 7075/graphite composites, *Composites: Part B*, 56, 2014, pp. 472–476.
8. Akhlaghi F., Zare-Bidaki A.: Influence of graphite content on the dry sliding and oil impregnated sliding wear behavior of Al 2024-graphite composites produced by in situ powder metallurgy method, *Wear*, 266, 2009, pp. 37–45.
9. Robertson J.: Amorphous carbon, *Solid State and material Science*, 1998, vol. 1, nr 4, pp. 557–561.
10. Bhoala N., Mehrotra R., Bragg R.H., Rao A.S.: Effect of treatment temperature (HTT) on density, weight and volume of glass-like carbon (GC). „*Journal of Materials Science*” 1983, vol. 18, pp. 2671–2678.
11. Myalski J.: Kształtowanie właściwości tribologicznych kompozytów zawierających węgiel szklisty, Gliwice, Wydaw. Politechniki Śląskiej, 2011.
12. Posmyk A., Myalski J., Hekner B.: Composite coatings with ceramic matrix including nanomaterials as solid lubricants for oil-less automotive applications, *Arch. Metall. Mater.*, 2016 vol. 61 iss. 2, pp. 1039–1043.
13. Olszówka-Myalska A.: Some Physicochemical Phenomena Observed During Fabrication of Mg-C Cast Composites, *Journal of Materials Engineering and Performance*, v. 25, 2016, pp. 3091–309.
14. Olszówka-Myalska A., Myalski J., Chrapoński J.: Influence of casting procedure on microstructure and properties of Mg alloy-glassy carbon particle composite, *Int. J. Mater. Res.*, 2015, vol. 106, no. 7, pp. 741–749.
15. Posmyk A., Myalski J., Hekner B.: Glassy carbon coating deposited on hybrid structure of composite materials, *Arch. Metall. Mater.* 2016 vol. 61 iss. 2, pp. 1045–1050.
16. Hekner B., Myalski J., Pawlik T., Sopicka-Lizer M.: Effect of carbon in fabrication Al-SiC nanocomposites for tribological application, *Materials*, vol. 10, iss. 6, 2017, pp. 1–15.
17. Myalski J.: Wpływ węglowej struktury szkieletowej na właściwości tribologiczne kompozytów z osnową aluminium, *Tribologia*, nr 5, 2015, pp. 89–98.
18. Myalski J., Hekner B.: Materiały kompozytowe o osnowie stopu aluminium umacniane pianami ceramicznymi, *Inżynieria Materiałowa*, 2015 r. 36, nr 5, pp. 220–224.
19. Myalski J., Hyla I., Śleziona J.: P-294493 pt.: Sposób wytwarzania węgla szklistego, 1994.