



Andrzej Posmyk<sup>1\*</sup>, Jerzy Myalski<sup>2</sup>

<sup>1</sup> Silesian University of Technology, Faculty of Transport, ul. Krasińskiego 8, 40-019 Katowice, Poland

<sup>2</sup> Silesian University of Technology, Faculty of Materials Engineering and Metallurgy, ul. Krasińskiego 8, 40-019 Katowice, Poland

\*Corresponding author: E-mail: andrzej.posmyk@polsl.pl

Received (Otrzymano) 30.01.2015

## PRECURSOR INFLUENCE ON TRIBOLOGICAL PROPERTIES OF METAL-CERAMIC COMPOSITES DESIGNED FOR AVIATION MACHINE PARTS

The paper presents the influence of the chemical composition and structure of a glassy carbon precursor on the tribological properties of a metal-ceramic composite, manufactured with the application of this precursor. Two groups of composites containing two different carbon precursors have been manufactured and studied. The first composite contained a glassy carbon precursor embedded from the liquid state in a porous ceramic foam with 90% open porosity. The ceramic foam ( $Al_2O_3$ ) is the reinforcing phase and the glassy carbon functions as a solid lubricant. A twofold increase in compressive strength was observed when the foam was present. The foam porosity was reduced to 85% after it was coated with carbon. However, it was good enough for proper infiltration with the liquid matrix alloy. In the case of the second composite, it is a spatial skeleton made of glassy carbon (RCV) which functions both as the reinforcement and solid lubricant. The open porosity of the carbon foam (95%) promoted good infiltration with the matrix alloy. There was no report of holes which were not filled with the matrix alloy within the entire volume of the samples subjected to microscopic tests. The wettability of the foam surface with the matrix alloy is sufficient enough to form strong bonds. The composite containing ceramic foam coated with glassy carbon showed better tribological properties than the composite which contained only carbon foam.

Keywords: hybrid composite, structure, precursor, glassy carbon, tribological properties, solid lubricant

## WPŁYW PREKURSORA NA WŁAŚCIWOŚCI TRIBOLOGICZNE KOMPOZYTÓW METALOWO-CERAMICZNYCH PRZEZNACZONYCH NA ELEMENTY LOTNICZE

Przedstawiono wpływ składu chemicznego i struktury przestrzennej prekursora węgla szklonego użytego do wytwarzania kompozytów metalowo-ceramicznych na ich właściwości tribologiczne. Wyprodukowano i przebadano dwie grupy kompozytów zawierających dwa różne prekursory węgla. Pierwszy kompozyt zawierał prekursor węgla osadzony ze stanu ciekłego na porowatej piance ceramicznej o porowatości otwartej 90%. Pianka ceramiczna ( $Al_2O_3$ ) pełni rolę umocnienia, a węgiel szklony rolę smaru stałego. Obecność pianki zwiększa wytrzymałość na ściskanie ponad dwukrotnie. Porowatość pianki po pokryciu węglem zmniejszyła się do 85%, ale jest wystarczająca do dobrej infiltracji ciekłym stopem osnowy. W drugim kompozycie rolę zarówno umocnienia, jak i smaru stałego pełni przestrzenny szkielec wykonany z węgla szklonego (RVC). Porowatość otwarta pianki węglowej (95%) pozwoliła na dobrą infiltrację stopem osnowy. W całej objętości przebadanych mikroskopowo próbek nie stwierdzono miejsc niewypełnionych stopem osnowy. Zwilżalność powierzchni pianki stopem osnowy jest wystarczająca do utworzenia trwałego połączenia. Wytrzymałość na ściskanie pianki węglowej (0,52 MPa) jest znacznie mniejsza niż pianki ceramicznej, dlatego właściwości kompozytu zawierającego tylko piankę węglową są gorsze. Podczas ciśnieniowej infiltracji ciekłym stopem osnowy dochodzi do lokalnych pęknięć i uszkodzeń struktury pianki. Drobne elementy pianki zostały przemieszczone. Generalnie, struktura pianki pozwoliła na uzyskanie równomiernego rozmieszczenia węgla szklonego w kompozycie. Właściwości tribologiczne kompozytu zawierającego piankę węglową we współpracy z żeliwem GJL-350 są gorsze niż kompozytu zawierającego piankę ceramiczną pokrytą węglem szklonym wytworzonym z ciekłego prekursora, którym nasączono porowatą piankę. Wytrzymałość na ścinanie pianki węglowej (30 MPa) jest porównywalna z wytrzymałością na ścinanie węgla szklonego wytworzonego podczas pirolizy prekursora osadzonego na piance ceramicznej. Powinno to wpłynąć na zmniejszenie współczynnika tarcia. Jednak małe wartości wytrzymałości na ściskanie powodują zagłębienie się trzpienia żeliwnego w kompozycie i pogarszają warunki współpracy ślizgowej.

Słowa kluczowe: kompozyty hybrydowe, struktura, prekursor, węgiel szklony, właściwości tribologiczne, smar stały

## INTRODUCTION

Due to their unique properties, composites find wide applications in the production of machine parts used in technical means of land, water, and air transport. Com-

posites are used to manufacture machine parts such as the fuselage for Boeing 747 and Airbus A350, Ferrari and Maserati racing car chassis as well as a variety of

subassemblies for average class cars in which brake discs, pistons, cylinders and chassis parts are made from composites.

Another group where composite materials find their application includes parts of machines operating in both sliding and friction contacts e.g., pistons for engines and compressors, piston rings, brake discs and brake drums. In the case of sliding contacts, friction is an undesirable phenomenon; therefore special criteria in designing composite properties should be taken into consideration. They should be different from those chosen in the case of materials designed for friction contacts. In general, when selecting the materials for sliding contacts, it is important to ensure the presence of engineering materials and operating materials - the first ones carry the load and the latter decrease the friction and wear.

Engineering materials should feature high resistance and hardness as well as high permissible pressure [1, 2]. An operating material should also be characterized by low shear stress. So far, the materials used in machine constructing could hardly meet all the requirements, whereas hybrid composite materials can perfectly do so. The matrix material and some kinds of reinforcing phase take over the function of engineering material. Additionally, the selected types of reinforcing phase function as operating material i.e., a solid lubricant.

Sub-assemblies in aviation transport are frequently based on materials with higher strength and lower density [2, 3]. High strength aluminium alloys with copper are used in cars and reciprocating engines of planes and thus the hybrid composites formed make it possible to increase the load and extend the operation time of such engines. The application of solid lubricants embedded in composites can contribute to engine reliability. Solid lubricants can be introduced into composites by various methods. One of them is based on a manufactured pre-form with a reinforcing phase and glassy carbon as a solid lubricant. Pre-form manufacturing requires the use of a precursor which can be produced from a variety of starting materials. The influence of the kind of glassy carbon precursor on the tribological properties of composite materials with an AlCu3Mg1 matrix alloy will be discussed in the article.

## MATERIALS

Due to the potential application of the investigated materials in the aviation industry, composites with a matrix alloy, widely used in aviation, were manufactured i.e., the AlCu3Mg1 alloy.

Two types of composites were produced i.e.:

- one containing a preform made of a ceramic reinforcing phase ( $\text{Al}_2\text{O}_3$ ) coated with glassy carbon (a solid lubricant);
- one containing a glassy carbon foam functioning as the reinforcing phase (hardness 6÷7 on the Mohs scale) and as a solid lubricant (shear strength 30 MPa).

The casts were produced in a pressure press by the infiltration of a pre-form coated with a carbon precursor and glassy carbon foam. The description of the production process of the composites and the precursor influence on their structure are presented in paper [1].

Composite samples were collected for tribological and microscopic tests. A pin with diameter  $d=3$  mm made of (GJL 350) cast iron used for combustion engine piston rings was used as the sample and a composite disc of a 30 mm diameter and 6 mm thickness was used as the counter-sample. The structures of the studied composites are presented in Figure 1.

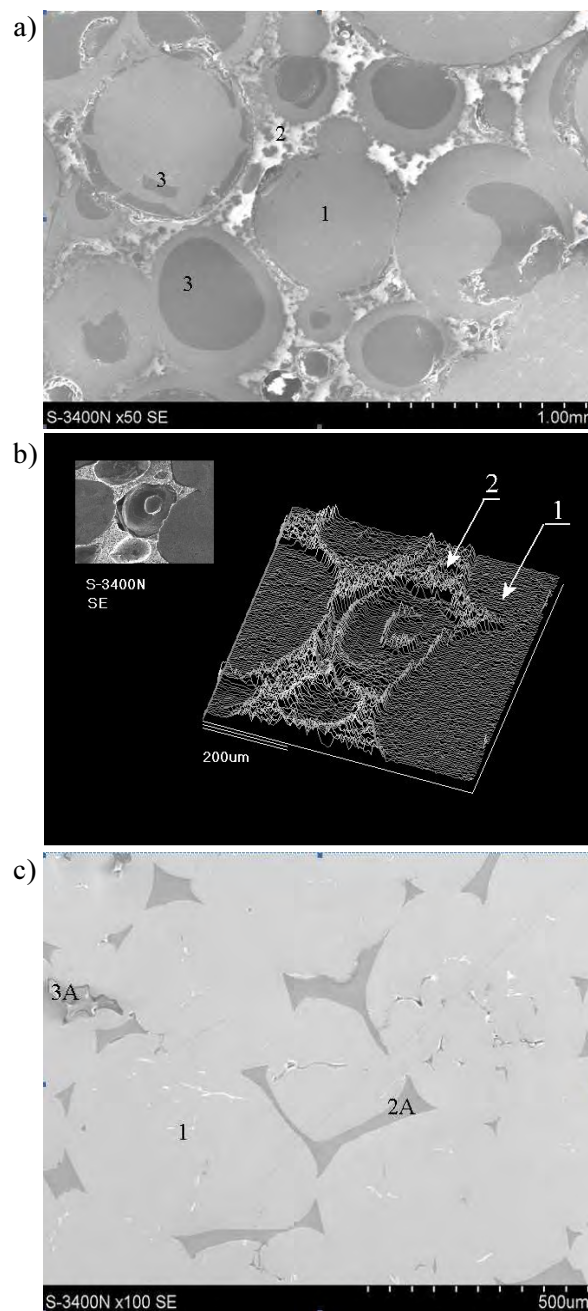


Fig. 1. Structure of composites containing precursor on  $\text{Al}_2\text{O}_3$  preform (a, b) and in carbon foam form (c): 1 - matrix, 2 -  $\text{Al}_2\text{O}_3$  foam, 3 - GC, 3A - pore

Rys. 1. Struktury kompozytów z prekursorem na preformie  $\text{Al}_2\text{O}_3$  (a, b) i w postaci pianki węglowej (c): 1 - osnowa, 2 - pianka  $\text{Al}_2\text{O}_3$ , 2A - pianka węglowa, 3 - WS, 3A - por

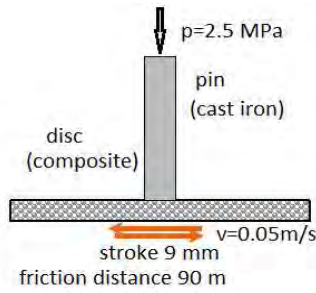


Fig. 2. Sliding contact of test stand for tribological examination

Rys. 2. Węzeł tarcia stanowiska do badań tribologicznych

**RESEARCH CONDITIONS AND RESULTS**

The tribological tests were performed in the reciprocating motion in friction in air with a tester simulating the sliding conditions of a piston ring-cylinder liner of an engine or piston compressor at a cold start. Such conditions are observed between a scraper ring and a cylinder liner during the cold start of engine. The diagram of the friction knot of the tester is presented in Figure 2. The results of the investigation are presented in Figures 3-8. The diagram of the friction coefficient and wear shows, for the sake of comparison, the test result of a composite containing only Al<sub>2</sub>O<sub>3</sub>. The samples after friction were then subjected to profilometric tests and SEM observations. Figures 5-8 present the results.

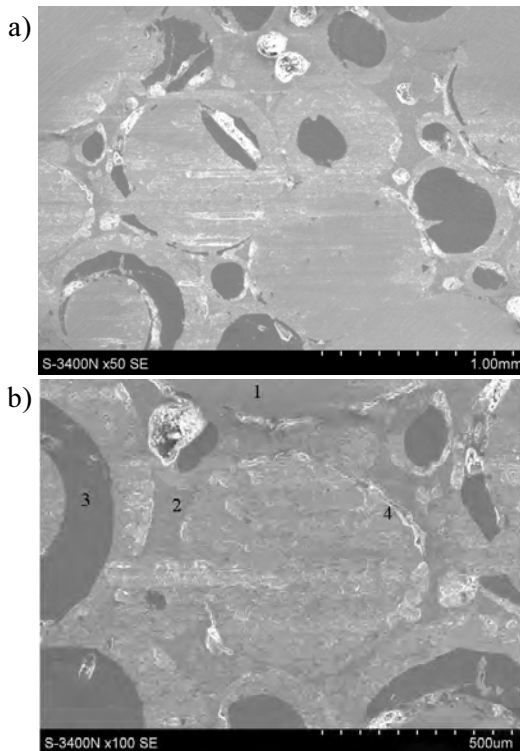


Fig. 3. Composite friction surface including Al<sub>2</sub>O<sub>3</sub> preform coated with glassy carbon: a) wearing-in stage, b) wear debris collected on ceramic-matrix border; 1 - matrix, 2 - Al<sub>2</sub>O<sub>3</sub>-foam, 3 - GC, 4 - wear debris

Rys. 3. Powierzchnie tarcia kompozytu zawierającego preformę z Al<sub>2</sub>O<sub>3</sub> pokrytą węglem szklistym: a) etap docierania, b) produkty zużycia na granicy ceramika-osnowa: 1 - osnowa, 2 - pianka Al<sub>2</sub>O<sub>3</sub>, 3 - WS, 4 - produkty zużycia

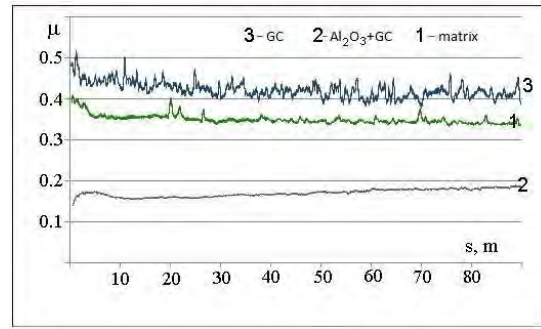


Fig. 4. Friction coefficient ( $\mu$ ) of investigated composites vs. sliding distance (s)

Rys. 4. Zależność współczynnika tarcia ( $\mu$ ) badanych kompozytów w funkcji drogi tarcia (s)

The investigation results proved that the composites with the Al<sub>2</sub>O<sub>3</sub> foam coated with glassy carbon are characterized by a very low value of friction in air coefficient ( $\mu < 0.18$  - line 2 in Fig. 4), lower by about 50% in comparison with the matrix material (line 1 in Fig. 4). Such a low  $\mu$  value allows the tested composite to be classified to the category of sliding materials.

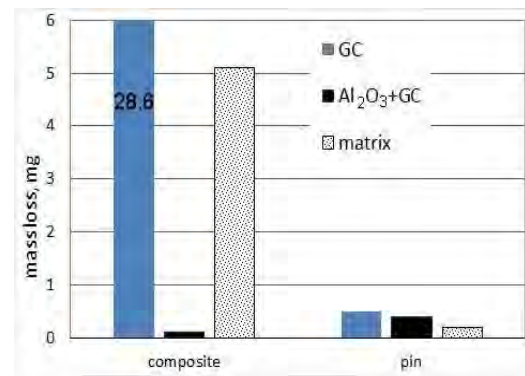


Fig. 5. Mass loss of investigated composites including reinforcing phase from different precursor after sliding against GJL-350 cast iron

Rys. 5. Ubytek masy badanych kompozytów zawierających fazę zbrojącą z różnych prekursorów po współpracy z żeliwem GJL-350

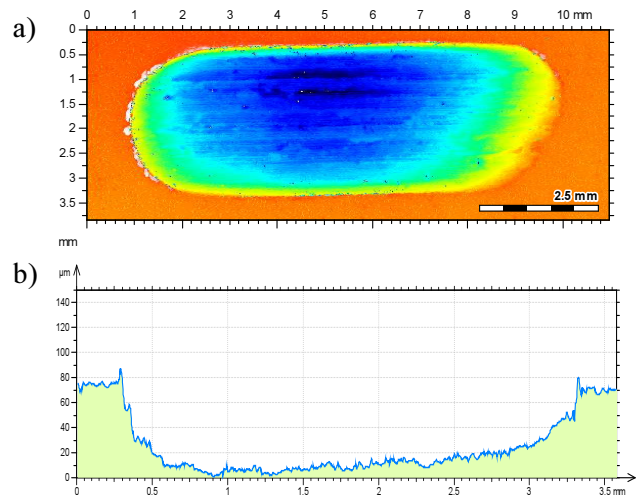


Fig. 6. Wear track of composite with Al<sub>2</sub>O<sub>3</sub>+C foam (a) and 2D roughness profile from wear track (b)

Rys. 6. Ślad zużycia kompozytu z pianką Al<sub>2</sub>O<sub>3</sub>+C (a) i profil 2D chropowości obszaru wytarcia (b)

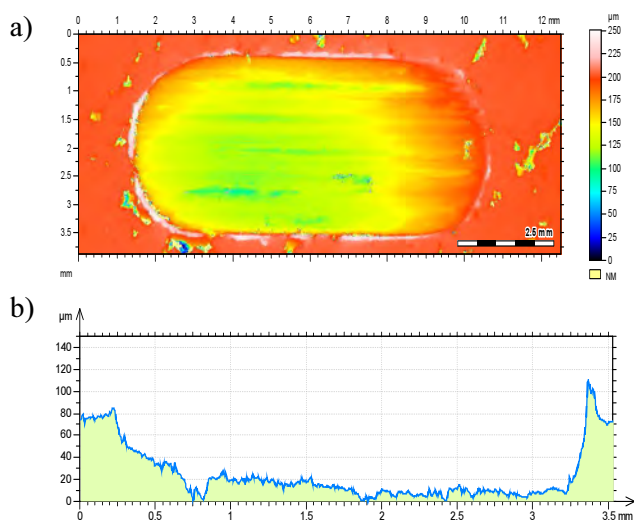


Fig. 7. Wear track of composite with carbon foam (a) and 2D roughness profile from wear track (b)

Rys. 7. Ślad zużycia kompozytu z pianką węglową (a) i profil 2D chropowatości obszaru wytarcia (b)

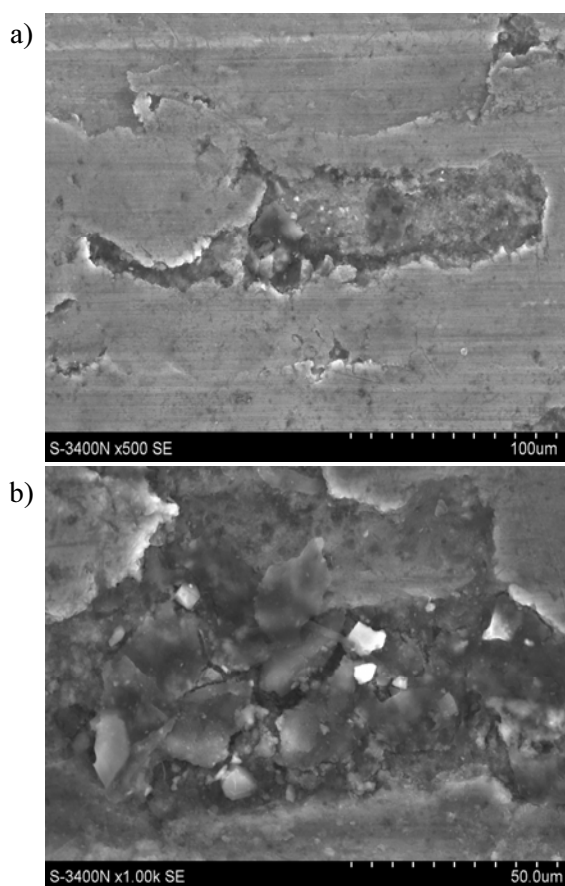


Fig. 8. Friction surface of composite with carbon foam: a) view, b) place after spalling of carbon foam part

Rys. 8. Powierzchnia tarcia kompozytu zawierającego piankę węglową: a) widok, b) miejsce po wykruszeniu fragmentu pianki węglowej

## DISCUSSION OF RESULTS

The friction coefficient value, in the case of the composite containing carbon foam, is found to be diverse ( $\mu = 0.4 \div 0.5$  - line 3 in Fig. 4), unstable and in

the final phase of friction it is very big, much bigger than in the case of the matrix material ( $0.4 \div 0.35$ ). At this stage of the investigations, it is very difficult to specify the cause of such behavior of a composite during friction. It might be the result of several factors, for example a lower content of reinforcing phase. The extensive porosity of the carbon foam (over 95%) reduces the reinforcing phase fraction, which is smaller than in the case of the composite with  $\text{Al}_2\text{O}_3$ . The initial porosity of the alumina foam is around 90%, and after it has been coated with glassy carbon this value falls to 85%. Thus the reinforcement phase fraction in the composite is doubled. During composite-pin material contact, friction occurs in the reinforcing phase and matrix. The surface after friction shows clear traces of light abrasive wear as well as wear caused by tacking adhesive bonding (Fig. 8a). Tacking of the matrix with the cast iron the pin is made of, takes place and as a result the pin is coated with an almost unbroken, regular film of wear debris (bright areas in Fig. 9b). The graphite in the cast iron is coated with this film and does not function as a solid lubricant. It causes an increase in the friction coefficient.

During rubbing of the pin against the composite, including the ceramic foam coated with glassy carbon, the graphite is exposed and enables the glassy carbon to act as a lubricant (black areas in Fig. 9a), which decreases the friction coefficient. A smaller amount of reinforcement phase as well as its lower stiffness (result of carbon foam mesh structure) escalates composite deformation and immersion of the pin into the composite (Fig. 7b). Such changes might also be stimulated by the distinctive microstructure of the foam. A sphere cell inside the carbon foam consists of connected rods forming a mesh arrangement similar to a fullerene structure. The sphere with a defined wall thickness inside the alumina foam is empty. The contact areas of the neighboring spheres are filled with ceramics (Figs. 1a and b). Therefore the edges forming carbon spheres inside the carbon foam undergo spalling more rapidly and are removed from the composite during friction (Fig. 8b). This happens despite strong bonds at the metal-carbon foam phase boundary. Wear debris is not disintegrated and is comparatively large in comparison with the  $\text{Al}_2\text{O}_3$  composite wear debris. The results of the wear tests seem to prove it as well. Such behaviour does not occur in the composite with the  $\text{Al}_2\text{O}_3$  foam coated with glassy carbon. Despite the carbon presence in the wear debris, the course of changes of the friction coefficient is different. According to literature data [4] and the authors' own investigations [1, 5-7] it can be stated that the presence of glassy carbon contributes to a lower and stabilized friction coefficient value ( $\mu = 0.4$  for matrix and  $\mu = 0.25$  for composite containing 50% glassy carbon particles). Additionally, it significantly reduces the wear of the rubbing materials.

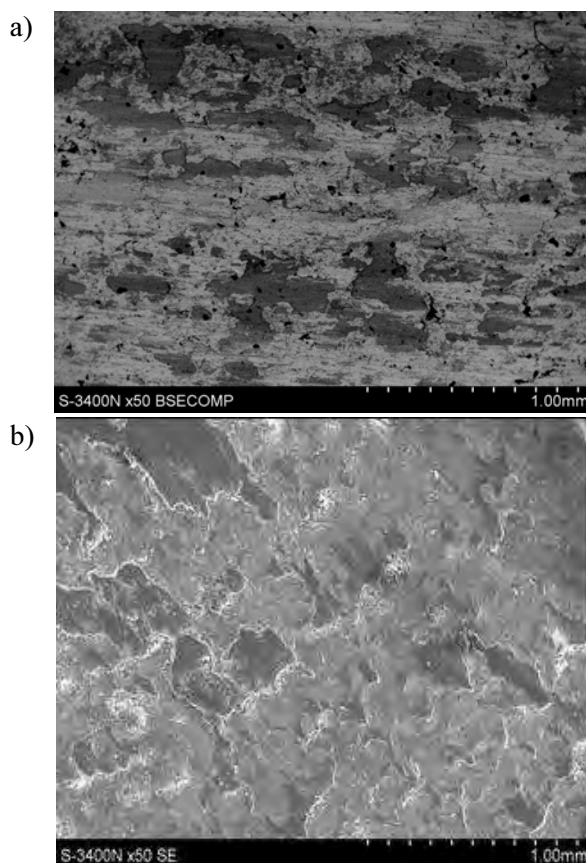


Fig. 9. Cast-iron pin surface after sliding against composite including ceramic preform (a) and carbon foam (b)

Rys. 9. Powierzchnia żeliwnego trzpienia po współpracy ślizgowej z kompozytem zawierającym preformę ceramiczną (a) i piankę węglową (b)

In the case of the cast iron-composite containing only carbon foam, the lubricating function of the glassy carbon is mitigated by the wear debris of the matrix material. These products form a kind of transfer film covering the glassy carbon in the composite (Fig. 8) and graphite in the cast iron (Fig. 9b). The slightly disadvantageous influence of the reinforcing carbon skeleton was observed in the wear investigations (Fig. 5). The wear of the composite with carbon foam was 6 times more excessive than that of the matrix material and 30 times larger than that of the composite with the aluminium oxide foam coated with glassy carbon. Low values of compression strength favour both plastic deformation of a composite and immersion of the cast iron pin in the composite. As a result, the sliding conditions deteriorate. Ploughing wear is predominant in the contact, the evidence of which is uplift of the material on the 2D roughness profile (Fig. 7b).

## CONCLUSIONS

On the basis of the carried out comparative studies on the influence of a glassy carbon precursor in

composites, it has been found that sliding composite materials with an embedded glassy carbon functioning as a solid lubricant can be obtained.

The composite with the AlCu3Mg1 matrix and the introduced ceramic foam as the reinforcement and the liquid carbon precursor, showed better tribological properties than the composite with glassy carbon foam only. Such a state resulted from the increased total fraction of the reinforcing phase i.e., of about 10% Al<sub>2</sub>O<sub>3</sub> and 5% carbon. The coefficient of friction in air had a value of 0.12÷0.18.

The composite with the AlCu3Mg1 matrix, which contained carbon foam (RVC) available on the USA market, is less pressure resistant since the foam has a low compressive strength ( $R_c = 0.5$  MPa [5]) and shows worse tribological properties. The pressure exerted by the cast iron pin causes plastic deformation of the composite, which leads to wear by ploughing. A composite with better tribological properties can be obtained if an alloy with a higher compressive strength is used.

## Acknowledgements

*Financial support of Structural Funds in the Operational Programme - Innovative Economy (IE OP) financed from the European Regional Development Fund - Project No POIG.0101.02-00-015/08 is gratefully acknowledged.*

## REFERENCES

- [1] Myalski J., Posmyk A., Precursor influence on structure of metal-ceramic composites designed for aviation machine parts. *Composite, Theory and Practice* 2015 (by Publisher).
- [2] Potoczek M., Gelcasting of alumina foams using agarose solutions, *Ceram. International* 2008, 34, 661-667.
- [3] Potoczek M., Myalski J., Ślężona J., Śliwa R., Ceramika porowata do infiltracji metalami wytwarzana metodą żelowania spienionej zawiesiny, *Inżynieria Materiałowa* 2009, 6 (172), 536-539.
- [4] Goller G., Koty D.P., Tewari S.N., Singh M., Tekin A., Wear and Friction Behavior of Metal Impregnated Microporous Carbon Composites, *Metallurgical and Materials Transactions A: Physical Metallurgy and Materials Science* 1996, 27, 3727-3738.
- [5] Method for production of aluminium-ceramic composite including solid lubricants, Patent application P. 398311 [WIPO ST 10/C PL398311] 2012.
- [6] Posmyk A., Myalski J., The influence of hybrid composites structure on their tribological properties, *Composites Theory and Practice* 2014, 1, 14, 18-22.
- [7] Posmyk A., Myalski J., Wistuba H., Properties of aluminium-ceramic composite with glassy carbon as solid lubricant designed for automotive applications, *Archives of Metallurgy and Materials* 2015.
- [8] Duocel Carbon Foam, ERG Materials and Aerospace Corporation, Oakland, CA, 2014.