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**PROPERTIES OF ALUMINIUM-CERAMIC COMPOSITE WITH GLASSY CARBON AS SOLID LUBRICANT DESIGNED FOR AUTOMOTIVE APPLICATIONS**

**WŁAŚCIWOŚCI KOMPOZYTU ALUMINIOWO CERAMICZNEGO ZAWIERAJACEGO WĘGIEL SZKLISTY JAKO SMAR STAŁY PRZEZNACZONEGO DLA MOTORYZACJI**

The paper presents some basic information on manufacturing, structure and selected properties of a new hybrid composite with an aluminium alloy matrix elaborated for automotive applications. A porous oxide ceramics constitute the reinforcing phase of the composite and glassy carbon plays the role of a solid lubricant. The properties of a composite, which contains exclusively a ceramic reinforcing phase and a hybrid composite with porous ceramics and glassy carbon, have been compared. The composite with glassy carbon, obtained by the application of new method, features uniform carbon distribution upon ceramics walls which significantly influences its tribological properties. The friction in air coefficient of a hybrid composite sliding against grey cast iron is 0.12, whereas in the case of a composite containing exclusively ceramics sliding against cast iron it amounts to 0.3.
*Keywords:* composite, aluminium matrix, glassy carbon, precursor, pyrolysis,

W artykule zaprezentowano podstawowe informacje nt. wytwarzania, struktury i wybranych właściwości nowego kompozytu hybrydowego z osnową ze stopu aluminium opracowanego dla potrzeb motoryzacji. Porowata ceramika tlenkowa stanowi zbrojenie kompozytu, a węgiel szklisty pełni rolę smaru stałego. Porównano właściwości kompozytu zawierającego tylko ceramiczną fazę zbrojącą z właściwościami kompozytu hybrydowego zawierającego porowatą ceramikę i węgiel szklisty. Kompozyt zawierający węgiel szklisty wytworzony dzięki nowej metodzie cechuje się jednorodnym rozłożeniem węgla na ściankach ceramiki, co wywiera istotny wpływ na właściwości tribologiczne. Współczynnik tarcia technicznie suchego kompozytu hybrydowego we współpracy ślizgowej z żeliwem wynosi 0.12, a kompozytu zawierającego tylko ceramikę wynosi 0.3.

## 1. Introduction

Composite materials with a light metal matrix find a wide range of applications in vehicle production due to their unique properties which are more advantageous than those of the matrix material. The improved properties feature [1,2,3]:

- up to 30% higher tensile strength and higher fatigue strength (30-50% after forging),
- higher wear resistance (several times),
- lower density when a porous reinforcing phase is used,
- a surface topography which facilitates lubrication.

Automotive elements made of composite materials with aluminium alloy matrices are used for producing vehicles and contribute to the reduction of their mass weight, fuel consumption and environmental pollution as well as an increasing of durability [4].

The literature provides a lot of information on manufacturing technology, structure as well as properties of composite materials [1-5]. The majority of currently manufactured AlMC composites are based on two technologies:

- mixing matrix material in a liquid state with properly prepared reinforcing phase,
- generating the reinforcing phase directly in matrix material as the result of chemical reactions.

Most often the reinforcing phase of these composites is made of $Al_2O_3$ or SiC particles or fibers. Some producers use flying ashes or rice hush ashes for reducing the composite density and producing costs. The presence of ceramic particles with sharp edges significantly reduces the wear of a composite when compared with that of a matrix material, but at the same time greatly intensifies the wear of its sliding partner, e.g., piston rings sliding against the composite cylinder liner of a combustion engine. Lower wear of a partner is achieved with the application of spherical particles of aluminium oxide [6].

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The least possible wear of a cast iron piston ring is achieved by the application of new generation composites with glassy carbon which were patented in 2008 [7,8]. Composites with glassy carbon particles feature such the wear of a sliding partner (cast iron for piston rings) which is similar to the wear of cast iron when sliding against composites containing $Al_2O_3$ fibers. These composites also demonstrate the lowest friction coefficient of all those materials tested by the authors [6]. Therefore, still new technologies for manufacturing this type of composite should be developed. The most difficult problem which has hindered the dissemination of the manufacturing technologies used so far was a non-uniform distribution of carbon particles.

Some constructions require a low density composite while keeping its other properties at the existing level. This requirement could be met by composites with foam materials, e.g., porous reinforcing particles [9-11] and porous particles with Cr [13]. Higher porosity reduces the density of composites and makes it possible to shape tribological properties of contacts where such composites have been used. One of the methods of lowering the friction coefficient and wear is an introduction of solid lubricants into the reinforcing particle pores. Silesian University of Technology in Gliwice together with the University of Silesia in Katowice have developed a new generation of hybrid composites in which the reinforcing phase is made of porous spheres of $Al_2O_3$ and the glassy carbon functions as a solid lubricant uniformly distributed within the entire volume of the composite [8,12]. The amount and properties of the introduced carbon influence tribological properties of the composite. This paper deals with the structure and selected properties of hybrid aluminium-ceramic composites with glassy carbon.

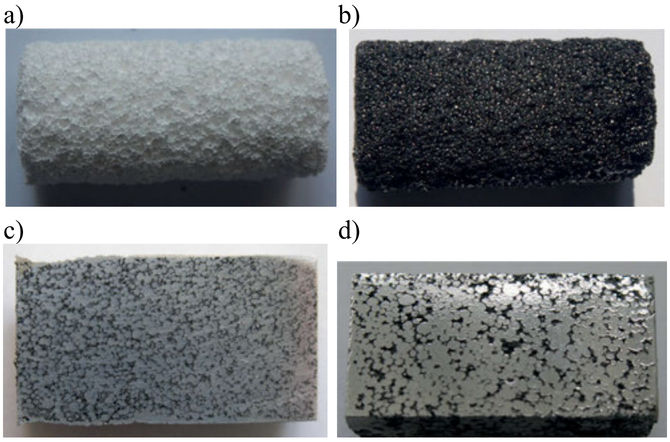



Fig. 1. Preform from porous ceramic foam before (a) and after (b) carbon introduction and after infiltration with AC-AlMg5 (c) and AC-AlCu3Mg1 (d) aluminium alloy

## 2. Materials and methods

By combining gelcasting of foams, nanotechnology of glassy carbon manufacturing and pressure infiltration, it was possible to elaborate a novel manufacturing technology of composites with aluminium alloy matrices reinforced with ceramics and glassy carbon. The essence of this technology is the ability to decrease the density and increase tribological properties of the composite through the application of hybrid reinforcement, e.g., foams from aluminium oxide filled with glassy carbon. Apart from aluminium alloys, other metal alloys such as magnesium or copper can be used as matrix materials. Preparation of these composites consists of the following steps [12]:

1. Manufacturing of ceramic foam with porosity of up to 90% which would ensure high wear resistance and reduce composite density (Fig 1(a)),
2. Foam saturation with a glassy carbon precursor which would guarantee low friction forces and low wear of sliding contacts,
3. Precursor pyrolysis in argon atmosphere (Fig 2),
4. Pressure infiltration with Al alloy penetrating the foam saturated with carbon (Figs 3-5).

More information on the composite production can be found in the patent description [12].

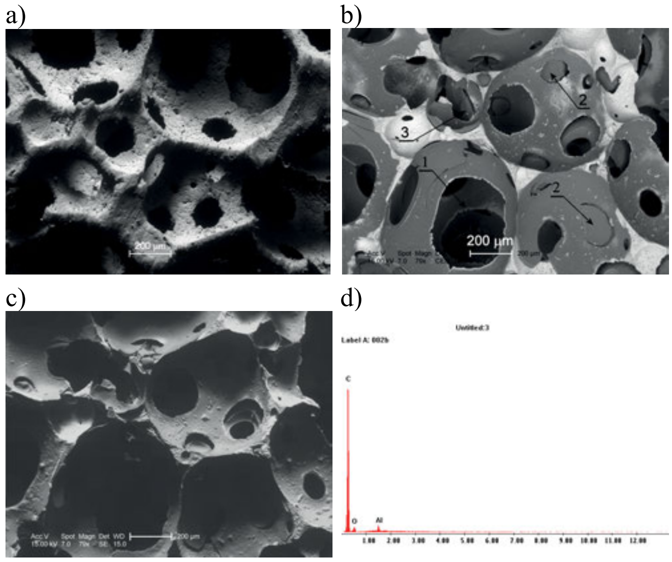



Fig. 2. Ceramic foam surface before (a) and after (b, c) carbon precursor introduction and its pyrolysis; element distribution (d), SEM: 1 – open pores for matrix infiltration, 2 – pores closed with glassy carbon, 3 – glassy carbon piece inside ceramic spheroid

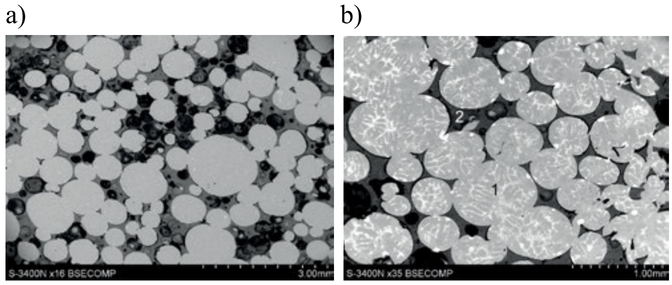
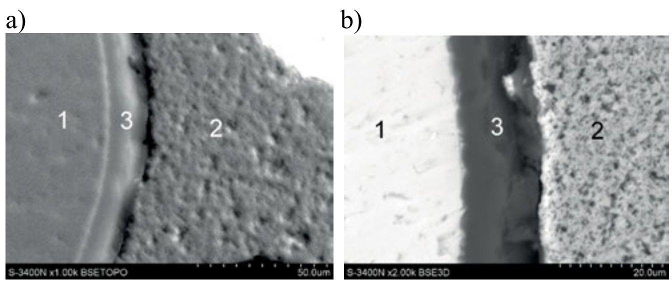



Fig. 3. Polished crosssections of examined composite with AC-AlCu3Mg1 matrix (a) and AC- AlMg5 matrix (b): 1- matrix alloy, 2- ceramic foam reinforcement



c) d)

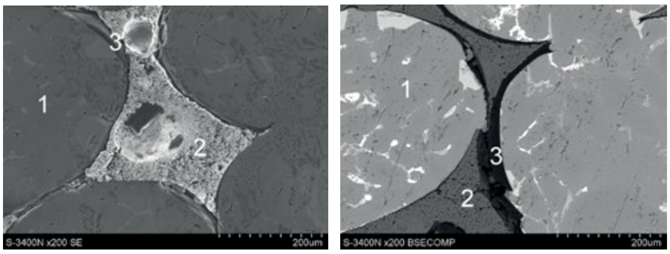



Fig. 4. Boarder zone between aluminium alloy and ceramic spheroid for composite with AlCu3Mg1 (a, c) and AlMg5 (b, d) alloy matrix: 1- matrix alloy, 2 – ceramic foam reinforcement, 3- glassy carbon coating on ceramic

a) b)

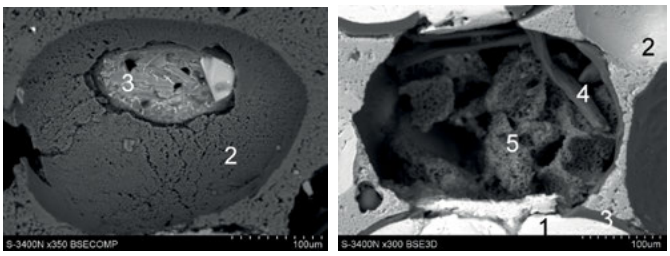



Fig. 5. Aluminia spheroid coated with GC film and filled with bundles of GC: a) oxide spheroid with remaining carbon film, b) oxide spheroid with glassy carbon bundles and ceramic splinters: 1- matrix alloy, 2 – ceramic foam reinforcement, 3 – glassy carbon coating on ceramic, 4 – glassy carbon ribbons in ceramic sphere, 5 – ceramic debris in ceramic sphere

## 3. Structure and selected composite properties

### 3.1. Structure

The structure and selected mechanical properties of composite materials, such as hardness and strength, determine their suitability for tribological purposes. The structure of manufactured composites was tested with the use of the scanning microscope on crosssections. Figs. 3, 4 and 5 present the results obtained. Composites with two matrices, e.g., AC-AlCu3Mg1 and AC-AlMg5 alloys, feature a uniform distribution of matrix, reinforcing phase and glassy carbon as a solid lubricant. Fig. 3 shows ceramic spheres filled with matrix alloys. The mean diameter of the spheres is variable; therefore, the diameters of elliptical matrix phases are not the same. From the point of view of mechanical properties such differences do not matter. From the tribological point of view, however, a uniform distribution of glassy carbon precipitates is of crucial importance. Fig. 4 shows the boundaries of the matrix alloy, glassy carbon and ceramic reinforcing phase. The figure shows that the GC films in the composite with AlMg5 and AlCu3Mg1 alloys matrices feature similar thicknesses, i.e., around 15 μm. The thickness of the glassy carbon film determines the lubrication during contact sliding. More glassy carbon results in lower friction forces and lower wear of sliding elements.

### 3.2. Compressive strength and wear resistance

Compressive strength (Rc) of the composites developed seems crucial because of their potential application in production of combustion engine elements and air compressors for automotive industry. Compressive strength tests were performed upon preforms prepared according to ISO 7500-1. The tested composite features Rc=219.4 MPa and rupture strain A=18.5% at matrix strength of Rc=50.5 MPa and A=47.1%.

a) b) c)

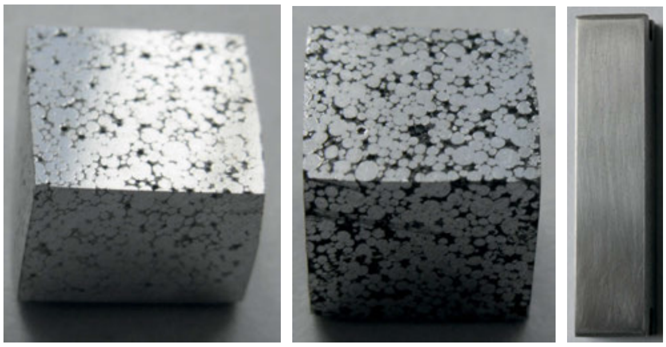
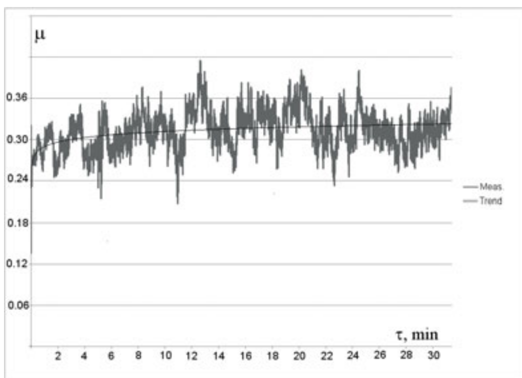


Fig. 6. Samples and counter-samples used for investigations: a) composite with ceramics, b) composite with ceramics and glassy carbon, c) GJL-350 cast-iron

Preliminary tribological research on two composite materials, the first one containing only $Al_2O_3$ foam and the second one containing $Al_2O_3$ foam coated with glassy carbon, were performed using reciprocating motion at a stand simulating the conditions of using oil-less air compressors and the cold start of piston machines, i.e., when oil viscosity is too high and splash lubrication is ineffective. Segments cut out of the piston skirt (cube of 10 mm side) and of the cylinder liner (cuboid 140x16x8 mm) constitute the friction contact (Fig. 6) at the stand. The investigations were performed under conditions of friction in air. Friction forces were measured at the relative velocity of v=2.5 m/s and unit pressure of p=2 MPa.

Comparative research on two types of composites was performed, it is: first which contains only matrix and ceramic oxide spheroids and second with matrix, oxide spheroids and glassy carbon. The research was designed to determine the effect of glassy carbon presence on tribological properties of the composites. The results obtained are presented in Figs. 7-10.

a)



b)

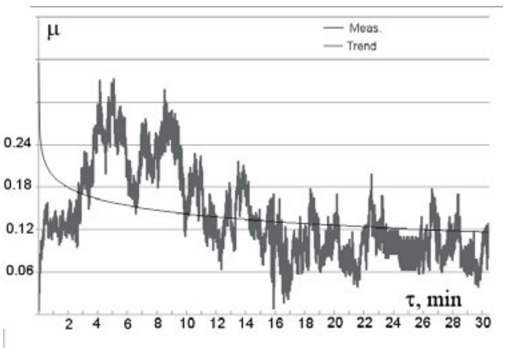



Fig. 7. Friction coefficient in composite/GJL-350 contact versus sliding time: a) composite without GC, b) composite with GC

a) b)

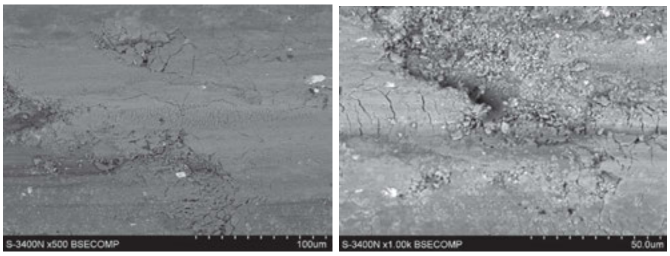


Fig. 8. Surfaces of composite without GC after sliding (cracks and crushes caused due to ceramic spheroid deformation)

a) b)

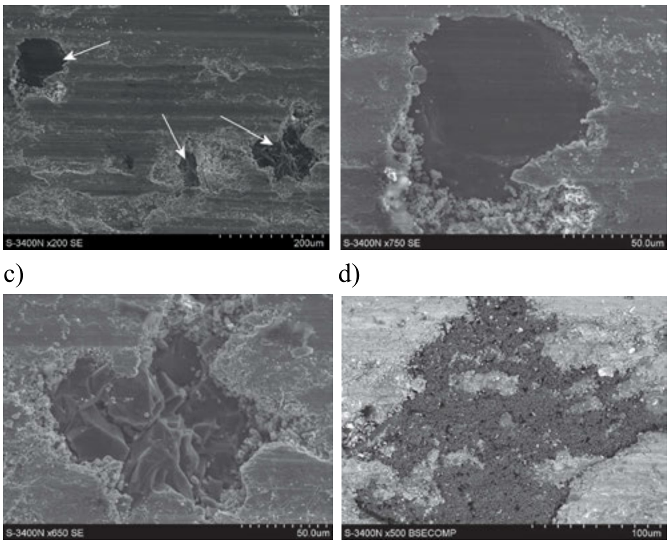


Fig. 9. Surfaces of composite with GC after sliding: ceramic spheroid with sliding traces (a and b) covered with GC and spheroid which don't take part in sliding (c) and spheroid with worn top (d): arrows show glassy carbon uncovered during friction

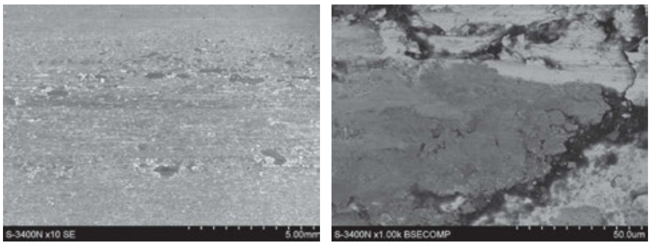


Fig. 10. Surfaces of the GJL-350 cast iron after sliding against composite material containing glassy carbon: a) general view, b) magnified part of Fig a

## 4. Discussion of the results

Figures 1 and 2 show the images that prove that the dimensions of pores in ceramic oxide foam are big enough for the carbon precursor to be introduced inside the spheroids. Moreover, the spaces between oxide spheroids enable the deposition of a precursor on their outer surface. This is proved by the results of qualitative analysis presented in Fig. 2(d). Technological assumptions of the pyrolysis process have been experimentally confirmed. As a result, glassy carbon was obtained from the deposited precursor. In the result of infiltration process conducted with two liquid matrix alloys, most of the spheroids (Figs 1(c), 1(d)) and spaces between them (Fig. 3) were filled which did not contribute to any visible changes in carbon films (Fig. 4). The thickness of the films amounts to over a dozen micrometers. Some spheroids have not been filled with matrix alloys. Carbon bundles and irregular ceramic fragments have been left inside which are visible on the crosssections obtained (Fig. 5) The most probable cause of such state might be the fact that small pores are closed by the carbon precursor during their annealing process after saturations (2-Fig. 2(c)). Another reason might be too low a pressure at infiltration with the liquid matrix alloy.

Strength properties of the matrix, the amount of glassy carbon, as well as its uniform distribution and the way it is bound with matrix material, determine tribological properties of the analyzed composite materials. In the composites developed, glassy carbon was found on the walls of ceramic spheroids in the form of continuous films and filled some of them with bundles (Fig. 5). Such distribution of glassy carbon, which functions as a solid lubricant, prevents adhesive tacking during sliding, e.g., with another aluminium alloy or cast iron.

Strength tests proved that when 10% alumina spheres were introduced into matrix aluminium alloy, the compressive strength increased (4.3 times) and plasticity decreased (2.5 times). Higher strength occurred as the result of joined spheroids which form a 3D skeleton plus the fact that they are filled with matrix alloy. During compression, movement of matrix alloy is braked by spheroids.

The tribological tests performed of composites sliding against cast iron in air showed that the presence of glassy carbon films upon walls of oxide spheroids lowered the friction coefficient from 0.3 for a carbon-free composite (Fig. 7(a)) to 0.12 (Fig. 7(b)) for a composite with carbon. Wear mechanism of the sliding elements is similar for both composites. Abrasive wear dominates in contact sliding. Cast iron is worn by hard oxide spheroids. During sliding of a composite which contains glassy carbon, wear products of carbon are deposited upon sliding surfaces (Figs. 9 and 10(b)) and alleviate friction. Some of the spheroids covered with carbon, which are located in friction zone (Figs. 9(a) and 9(b)), are the source of solid lubricant which lowers the friction forces. Spheroids placed below the contact surface do not take part in the friction (Figs. 9(c) in the wearing in stage or take part only on their tops 9(d)). In the early minutes of contact, some small walls of oxide crush and are included into cast iron (Fig. 10(a)). These small splinters cause abrasive wear of a composite. After about 20 minutes of sliding, ceramic wear debris are removed from the friction zone and GC wear debris form a very thin transfer film on the cast iron surface (Fig. 10b) and the friction coefficient stabilizes (Fig. 7(b)).

In the contact with a glassy carbon-free composite, after several minutes the friction coefficient reaches a value 0.3 and does not change over the entire test time. This accounts for the homogenous structure of the composite. Spheroids which have not been filled completely with matrix and are located directly under the contact area, crack as the result of deformation and subside pulling the matrix material inside, which is manifested by arc cracks (Fig. 8).

## 5. Conclusions

1. As the investigations show, it is possible to produce hybrid composites with an aluminium alloy matrix reinforced with ceramic spheres covered with glassy carbon. The production process for such composites consists of three stages: production of foam ceramics with 90% porosity, its saturation with glassy carbon precursor and precursor pyrolysis and finally pressure infiltration with the liquid matrix alloy. The process designed in such a way makes it possible to obtain a composite with a uniform distribution of glassy carbon over the entire volume which greatly improves tribological properties of the composite.
2. The technologies applied so far for the production of composites with glassy carbon require stirring of the suspension and do not guarantee uniform carbon distribution. This seems to be the most significant disadvantage increasing the frictional resistance during sliding, e.g., with cast iron, since local tacking with matrix alloy is possible to occur.

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