Andrzej Posmyk[1*], Jerzy Myalski[2]

[1] *Silesian University of Technology, Faculty of Transport, ul. Z. Krasińskiego 8, 40-019 Katowice, Poland*
[2] *Silesian University of Technology, Faculty of Materials Engineering and Metallurgy, ul. Z. Krasińskiego 8, 40-019 Katowice, Poland*
Corresponding author. E-mail: andrzej.posmyk@polsl.pl

COMPOSITES INCLUDING FOAM INSERTS DESIGNED FOR COMBUSTION ENGINE CYLINDER LINERS

The paper presents the influence of the reinforcing phase form on the structure and tribological properties of composites with an aluminum alloy (AlMg5) matrix containing glassy carbon as a solid lubricant. These composites are designed to produce cylinder liners of piston machines, namely air compressors, combustion engines and pneumatic actuator cylinders. The results of comparative examination of composites containing foam inserts made of Al_2O_3 coated with glassy carbon and composites containing foam inserts made from glassy carbon are presented. Adding Al_2O_3 foam to the AlMg5 alloy increases the compressive strength, but enhances the friction and wear of the sliding cast iron. The wear of the composite containing Al_2O_3 when rubbing against a pin made of cast iron GJL-250 is more than twice lower than the matrix. The presence of glassy carbon foam reduces the friction and wear of both the cast iron pin (more than five times) and the matrix. The presence of the Al_2O_3 foam in the AlMg5 alloy deteriorates the heat dissipation, causing an increase in temperature in the friction zone during friction in air against GJL-250 cast iron. The temperature in the friction zone of the composite with Al_2O_3 foam is more than 20°C higher than the friction zone of the composite comprising glassy carbon foam.

Keywords: alumina foam, glassy carbon, cylinder liner, friction, wear, composite

KOMPOZYTY Z PIANKOWYMI WSTAWKAMI PRZEZNACZONE NA TULEJE CYLINDROWE SILNIKÓW SPALINOWYCH

Przedstawiono wpływ postaci fazy zbrojącej na budowę i właściwości tribologiczne kompozytów na osnowie stopu aluminium (AlMg5) zawierającego węgiel szklisty jako smar stały. Kompozyty te są przewidziane do wytwarzania tulei cylindrowych maszyn tłokowych, tj. sprężarek powietrza i silników spalinowych oraz cylindrów siłowników pneumatycznych. Przedstawiono wyniki badań porównawczych kompozytu zawierającego wstawki wykonane z pianki Al_2O_3 pokrytej węglem szklistym oraz kompozytu zawierającego wstawki z pianki wykonanej z węgla szklistego. Dodanie do stopu AlMg5 pianki Al_2O_3 zwiększa jej wytrzymałość na ściskanie, ale intensyfikuje tarcie i zużycie współpracującego z nim żeliwa. Zużycie kompozytu zawierającego Al_2O_3 podczas współpracy z trzpieniem z żeliwa GJL-250 jest ponad 2-krotnie mniejsze niż z osnowy. Obecność pianki z węgla szklistego zmniejsza tarcie i zużycie zarówno trzpienia żeliwnego (ponad pięciokrotnie), jak i osnowy. Obecność pianki Al_2O_3 w stopie AlMg5 pogarsza warunki odprowadzania ciepła, powodując wzrost temperatury w strefie tarcia, w warunkach tarcia technicznie suchego z żeliwem GJL-250. Temperatura w strefie tarcia kompozytu z zawartością pianki Al_2O_3 jest ponad 20°C wyższa niż w strefie tarcia kompozytu zawierającego piankę z węgla szklistego.

Słowa kluczowe: pianka z tlenku aluminium, węgiel szklisty, tuleja cylindrowa, tarcie, zużycie, kompozyt

INTRODUCTION

Cylinder liners of piston machines, e.g. compressors and internal combustion engines are subjected to a complex state of loads during the operation of these machines. The walls of the liner are exposed to mechanical load coming from the pressure of exhaust gases (F_P and F_{PS}, Fig. 1) and the elasticity of the piston rings (F_{PR}) as well as heat load resulting from the difference in the exhaust gas temperature (T_G) throughout the entire combustion cycle (from the temperature of the intake air to the temperature of the exhaust gas), and coolant temperature (T_{CL}) filling the wet engine block. For these loads, there are also friction forces (F_F)

whose values depend on the pressure forces and the lubrication conditions. Mechanical loads cause bending of the cylinder liners walls, which at excessively large differences in stiffness of the matrix material, and inserts, may lead to loss of cohesion between them and thermal conductivity deterioration. Heat load increases the compressive stress due to expansion of the liner material.

The temperature difference ($\Delta T = T_G - T_{CL}$) on both sides of the walls of the liner can be reduced by increasing the thermal conductivity of the liner material (λ). Poor heat transfer by the liner raises the temperature of

the sliding surface, which adversely affects lubrication by reducing the viscosity of the oil. Therefore, the preferred solution is to make the liner from a hybrid composite, i.e. composed of two reinforcing phases. The task of one of them is to support the activities of oil lubrication by introducing a solid lubricant to the liner material.

A solid lubricant provides a defined friction coefficient almost independent of the temperature. The task of the second, the strengthening phase, is to increase the wear resistance. If the material of the strengthening phase is characterized by high compressive strength and low shear strength, it can also increase the wear resistance and reduce friction. Such materials may include foams made of glassy carbon (GC) [1, 2]. It is hard enough (the micro hardness of porous GC is $18 \div 20$ MPa and non-porous is $200 \div 340$ MPa) to reduce wear and has a low shear strength (30 MPa) to reduce friction.
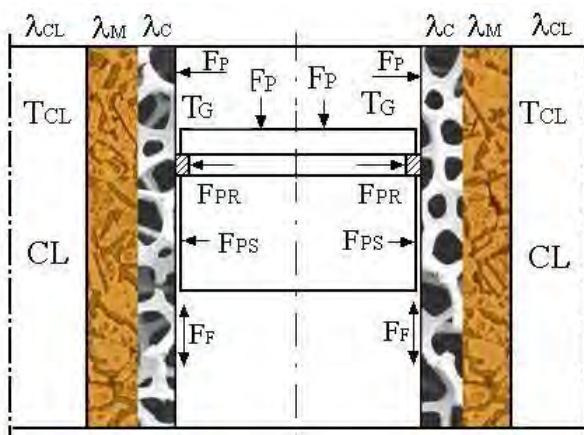

Fig. 1. Contact model of piston/cylinder liner with hybrid composite insert containing a reinforcing-lubricating phase: λ - thermal conductivity, C - composite, M - matrix, CL - cooling liquid, F_{PR} - force of piston elasticity, F_{PS} - force of piston skirt load, F_P - combustion gases force, T_{CG} - combustion gases temperature, T_{CL} - cooling liquid temperature

Rys. 1. Model skojarzenia tłok/tuleja z wkładką wykonaną z hybrydowego kompozytu zawierającego fazę umacniająco-smarującą: λ - przewodność cieplna, C - kompozyt, M - osnowa, CL - płyn chłodzący, F_{PR} - siła sprężystości pierścienia, F_{PS} - siła nacisku płaszcza tłoka, F_P - siła od ciśnienia spalin, T_{CG} - temperatura spalin, T_{CL} - temperatura płynu chłodzącego

The production of a cylinder liner comprising two reinforcing phases, i.e. serving as a strengthener e.g. Al$_2$O$_3$ or SiC and as a lubricant e.g. glassy carbon or graphite by commonly used methods of mixing is difficult because of the differences in density ($\rho_{GC} = 1500$ kg/m^3), hindering uniform arrangement of the reinforcing phase (RP) particles in the entire volume of the cylinder liner or insert. It is interesting from the technological point of view to use preforms made of ceramic foam coated with a GC layer, or GC foams.

This article is dedicated to the structure and comparison of selected properties of composites containing inserts made of Al$_2$O$_3$ foam coated with GC and foam made of glassy carbon.

PREPARATION OF MATERIALS

In order to check the suitability of the elaborated technology for producing composites containing a reinforcing phase that serves two functions, i.e. to strengthen the matrix material and to improve the tribological properties, tests were performed on two composite materials containing inserts made of Al$_2$O$_3$ foam coated with glassy carbon and foams made from glassy carbon. In the first composite Al$_2$O$_3$ foam is the strengthener, and glassy carbon is the solid lubricant. In the second composite glassy carbon foam performs both functions.

In the study two types of preforms were used; the first was made of Al$_2$O$_3$ coated with glassy carbon and the second made of glassy carbon. The Al$_2$O$_3$ foam was made by gelling foamed slurry [3]. This process consisted in heating a suspension of α-Al$_2$O$_3$ and mixing it with an aqueous solution of agarose [4]. Then, after introducing the foaming agent, the foam was made by mixing in a cooled closed mold. The resultant spatial structures were sintered for 2 hours at 1550°C. After sintering the foams were impregnated with a glassy carbon precursor and subjected to pyrolysis. The porosity of the produced foams is about 90% at a density of 250 kg/m^3. The average porosity of the cells measured in terms of pore per inch (ppi) was in the range of $40 \div 60$ ppi, and the diameter of the windows in the foam cells was about 10 μm, which sufficiently assured the liquid metal infiltration process.

The carbon foams used in the examination were prepared by the authors' own method [3]. The process involves initial coating of the polymeric foam by phenol formaldehyde resin and its carbonization in a vacuum oven at 1000°C for 24 hours. The resulting spatial structures of the glassy carbon are characterized by an open porosity of more than 85%, which influences the liquid metal infiltration process. The diameter of the carbon foam cells depends on the structure of the used polymer foam. For the study foams with a density of about 150 kg/m^3, cell diameter of about 150 μm and diameter of the windows in the cells of $20 \div 50$ μm were used. The thickness of the carbon cell walls does not exceed 15 μm, which reduces the compressive strength, compared with Al$_2$O$_3$ foams. The porosity was about 40 ppi. The preformed foams with a high porosity were subjected to infiltration with liquid aluminum alloy containing 5% Mg, 0.1% Mn and small amounts of Cr, Si and Mn less than 0.1% (AlMg5). The process was carried out in inductively heated Degussa press graphite shells (720°C, 2 MPa), giving the possibility to correctly fill in the ceramic structures with the matrix material. Al alloy heated above its melting temperature and low pressure infiltration allowed filling of the channels formed between the structure of the ceramic fittings, without destroying it. This was particularly important in the case of preforms made of glassy carbon characterized by several times lower compressive strength (~2 MPa) than the foams made from Al$_2$O$_3$ (~8 MPa). A too high pressure of infiltration leads to exceeding of

the value of maximum compressive stress of the foam material, and destruction of the cell wall skeleton of spatial structures. Destruction of the skeletal structure contributes to changes in the distribution of reinforcement in the composite, causing disorder in the structure of the foam cells, hindering the process of infiltration. This also contributes to uneven distribution of the strengthening phase in the composite structure to form areas of increased concentration of the glassy carbon.

MICROSCOPIC EXAMINATION

In order to verify the correctness of the structure of the composite with glassy carbon foam, microscopic examination of polished cross-sections was performed. In order to clarify the wear mechanisms of the composite, microscopic examination of its surface after sliding against a cast iron pin was performed. The results are shown in Figures 2, 3 and 7.
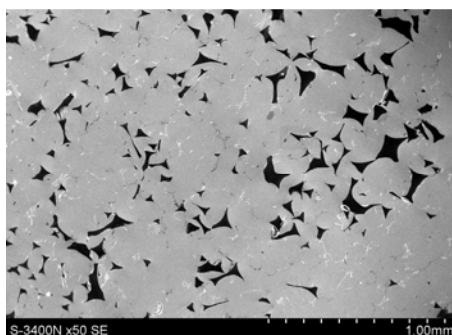

Fig. 2. View of polished cross-section of composite with GC-foam (SEM)
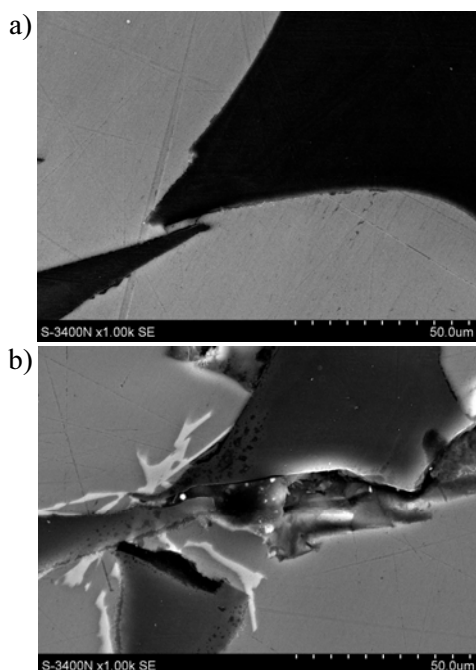Rys. 2. Widok z powierzchni zgładu kompozytu z pianką WS (SEM)

Fig. 3. Border between matrix and GC foam rod with good connection (a) and with loosening (b)
Rys. 3. Granica między osnową i prętem pianki z WS z dobrym połączeniem (a) i odspojeniem (b)

TRIBOLOGICAL EXAMINATION

In order to examine the effect of the reinforcing phase on the friction force and heat conduction values, tribological tests in air on two contacts were conducted. The specimen was made of a cast iron (GLJ-250) pin (Fig. 4a) and the counter specimens were disks made of a composite containing Al_2O_3 foam coated with glassy carbon as well as a composite containing glassy carbon foam. In the pin, four holes at distances of 1.5, 3.0, 4.5 and 6.0 mm from the sliding surface were made in which thermocouples were placed. Figure 4b shows the friction contact with fixed thermocouples. The test was conducted under the following conditions: pressure $p = 1$ MPa, sliding velocity $v = 0.5$ m/s, sliding distance $s = 1000$ m. The test was repeated three times.
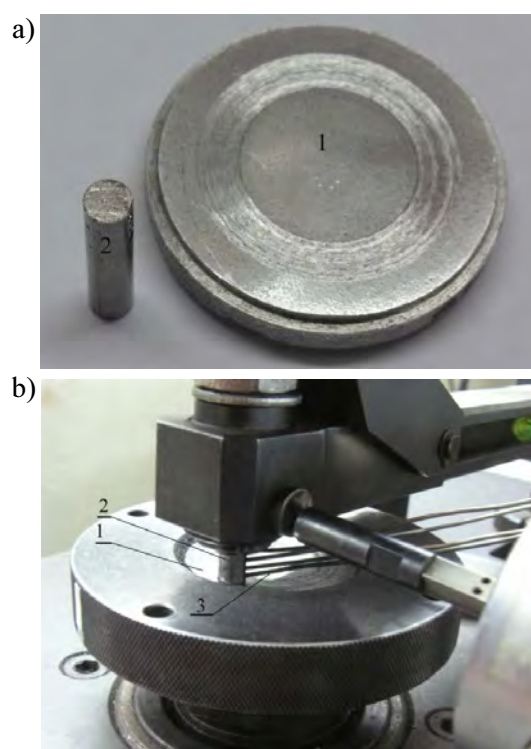

Fig. 4. View of friction contact with thermoelements: 1 - composite disc, 2 - GJL-250 pin, 3 - thermoelements
Rys. 4. Widok węzła tarcia z termoparami: 1 - kompozytowa tarcza, 2 - trzpień GJL-250, 3 - termopary

During the experiments, friction force, temperature at 4 points in the pin and mass loss of the pin and disc were measured. The friction forces were measured and registered using a strain gauge force transducer with an inaccuracy of 3%. The temperature near the friction zone was measured and registered by means of K type thermocouples with a measuring inaccuracy of 5%. The achieved results are presented in Figures 5, 6 and Table 1.

In order to compare the effect of the reinforcing phase material distribution on the structure and tribological properties, the test results of two composites - with Al_2O_3 foam coated with a glassy carbon layer, and with foam made of glassy carbon are given.
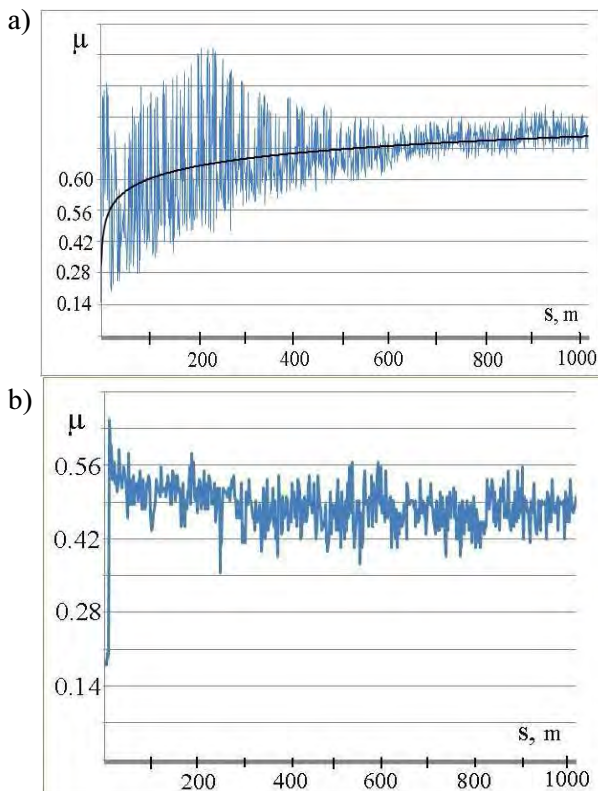
a)

b)

Fig. 5. Friction coefficient vs. sliding distance in GJL-250/composite contact with Al_2O_3-foam coated with GC (a) and with GC-foam (b)

Rys. 5. Zależność współczynnika tarcia od drogi tarcia w skojarzeniu GJL-250/kompozyt z pianką Al_2O_3 pokrytą warstwą WS (a) i z pianką z WS (b)
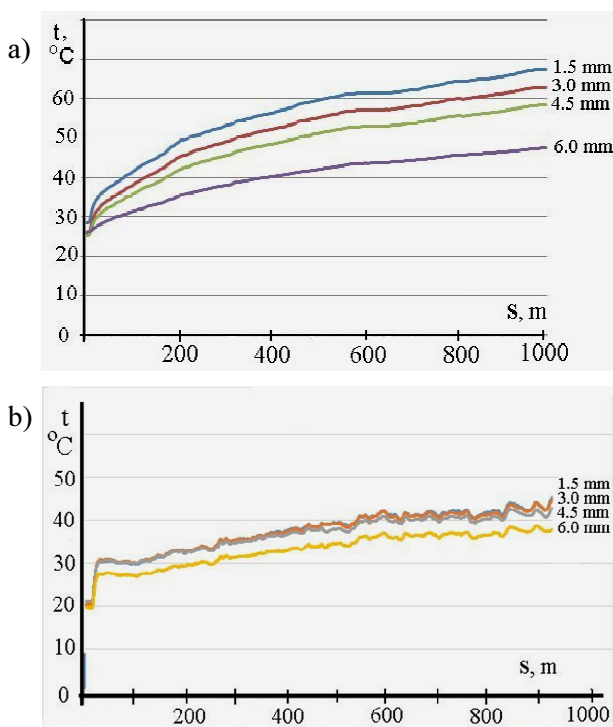
a)

b)

Fig. 6. Temperature in cast iron pin depending on distance from contact surface vs. sliding time against composite with Al_2O_3 foam coated with GC (a) and against composite with GC foam (b)

Rys. 6. Temperatura w trzpieniu żeliwnym w odległości od powierzchni tarcia w funkcji czasu współpracy z kompozytem z pianką Al_2O_3 pokrytą WS (a) i z kompozytem z pianką z WS (b)

Material Wear [mg]	Matrix	$M+Al_2O_{3F}+GC$	$M+Al-GC_F$
Pin	1.7	4.7	0.8
Disc	18.3	9.2	12.6

DISCUSSION OF RESULTS

On the basis of microscopic examination of the elaborated composite, its technological correctness can be confirmed. The molten alloy matrix material wetted the walls of the glassy carbon foam, providing good connection thereof (Figs. 2 and 3a). Places with loosening between the GC and the matrix (Fig. 3b) can occasionally be found.

Comparing the friction coefficient value and temperature of the pin in the vicinity of the friction zone, a significant impact of the glassy carbon forms on the tribological properties can be observed. The coefficient of friction in contact with the composite containing Al_2O_3 foam coated with glassy carbon has a rising tendency and at the end of the studies (800÷1000 m) it exceeds 0.65 (Fig. 5a). This is due to the wear of the thin film of glassy carbon exposing the Al_2O_3 foam, its chipping and the appearance of crumbled oxide foam debris as additional wear products between the composite and cast iron.
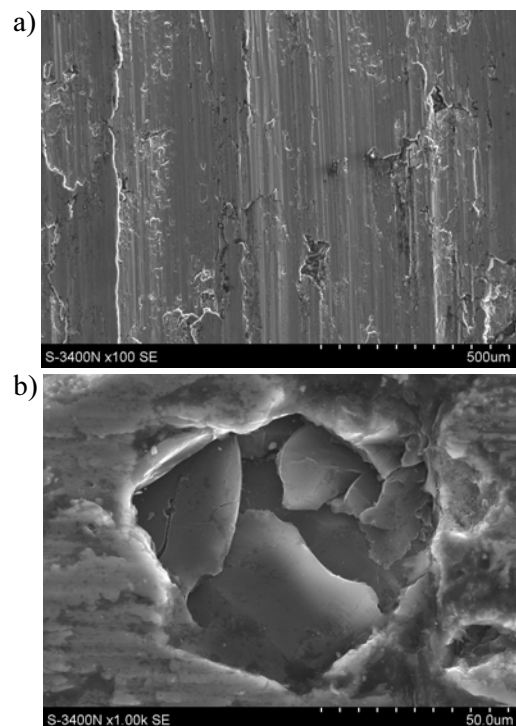
a)

b)

Fig. 7. Surface of composite after sliding against GJL-250: a) view, b) revealed GC parts (SEM)

Rys. 7. Powierzchnia kompozytu po współpracy z GJL-250: a) widok, b) odsłonięta część WS (SEM)

In the contact with the glassy carbon foam, the friction coefficient decreases from 0.56 to about 0.48 (Fig. 5b). This is caused by exposing the glassy carbon foam parts (Fig. 7b), and platting the wear debris on the sliding surfaces (dark streaks on the matrix alloy in Figure 7b). The temperature in the cast iron pin rubbing against the first composite (Al_2O_{3F}+GC) is significantly higher (68°C, Fig. 6a) than in the contact with the composite that includes glassy carbon foam (43°C, Fig 6b)). The thermal conductivity of glassy carbon (λ_{GC} = = 4.6÷6.3 W/(mK)) is less, while the specific heat (c_{wGC} = 1260 J/(kgK)) is higher than that of Al_2O_3 (λ_{Al2O3} 30 W/(mK); c_{Al2O3} = 850 J/(kgK)). The lower specific heat of Al_2O_3 causes higher temperature increases during friction. The lower temperature in contact with the composite with GC foam is caused by the lower coefficient of friction. The wear of the composite containing Al_2O_2 foam coated with GC is approximately 35% lower than that of the composite with GC foam. This is due to the lower compression strength of the GC foam, than the Al_2O_3 foam+GC. On the other hand, the wear of the cast iron pin sliding against the first composite is more than five times higher than against the composite reinforced by GC. This is due to the abrasive wear of the cast iron by aluminum oxide. The pin surface after sliding against the composite with Al_2O_3 foam is shiny with distinct scratches of abrasive wear. On the surface of the pin after friction against the composite with GC foam, a sliding film from the wear products was formed, thus reducing the wear of the pin.

Strengthening AlMg5 alloy with Al_2O_3 foam coated with GC reduced its wear, but increased the wear of the cast iron pin. It is a result of abrasive acting aluminum oxide foam. Strengthening of this alloy with GC foam reduces the wear of both the composite and the cast iron pin sliding against it.

Tribological tests were conducted under friction in air conditions. Such conditions prevail in the cylinder liners of oil-free air compressors or in pneumatic actuator cylinders. In compressors, the sliding partner of cylinder liners are composite piston rings, e.g. made of polyurethane filled with solid lubricants (PTFE, graphite). In pneumatic actuators cylinder liner slides against rings made from butadiene-acrylonitrile rubber filled with solid lubricants. The presence of additional amounts of solid lubricant in the rings reduces the friction forces.

In combustion engines, cast iron piston rings slide against the composite liner, with the presence of oil. The structure of the composite containing preforms made of GC foam gives a large number of reservoirs of oil, mixed with GC wear debris from the composite and graphite from the cast iron, which will contribute to improving the lubrication conditions. In order to check the influence of preforms made of GC on lubrication, examination of contacts lubricated with engine oil will be performed in the next stage.

CONCLUSIONS

Based on the results of the examinations the following conclusions can be drawn:

1. By introducing to the AlMg5 alloy Al_2O_3 foam which serves as a strengthener, coated with a layer of glassy carbon, which acts as a lubricant, reduces the wear of the composite, but it increases the wear of a sliding pin made of GJL-250 cast iron and the temperature in the zone of friction in air.

2. By introducing to the AlMg5 alloy glassy carbon foam in its role to act as a strengthener and solid lubricant, reduces the intensity of friction during sliding against GJL-250 cast iron, which is reflected by a decrease in the coefficient of friction and temperature in the friction zone.

REFERENCES

[1] Posmyk A., Myalski J., Hekner B., Glassy carbon coating deposited on hybrid structure of composite materials, Archives of Metallurgy and Materials 2016, 61, 2B, 145-150.

[2] Myalski J., Hekner B., Posmyk A., The influence of a skeletal carbon structure on the tribological properties of composite with an aluminium matrix, Tribologia 2015, 5, 89-97.

[3] Metod for production of aluminium-ceramic composite including solid lubricants, Patent Application P.3983.

[4] Potoczek M., Gelcasting of alumina foams using agarose solutions, Ceram. International 2008, 34, 661-667.

[5] Posmyk A., Myalski J., Designing of cylinder liners made from hybrid composites containing solid lubricants, Composites, Theory and Practice 2016, 16, 1, 15-19.