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PRECURSOR INFLUENCE ON STRUCTURE OF METAL-CERAMIC COMPOSITES DESIGNED FOR AVIATION MACHINE PARTS

The paper presents the influence of the spatial structure of a glassy carbon precursor on the structure and properties of sliding composites. Comparative studies carried out and the results obtained have been described for composites containing conventional carbon foam as well as those containing glassy carbon foams, from various types of glassy carbon precursors, functioning as reinforcement and a solid lubricant. The application of two different reinforcing phases based on the different types of precursors used, results in producing composites of varied structures and properties. Such a procedure also requires a pressure change in precursor infiltration. The material used for production of the carbon precursor as well as the process parameters of its pyrolysis allow significant modification of the structure and properties of the manufactured composite.

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

WPLÝW PREKURSORA NA STRUKTURĘ KOMPOZYTÓW METALOWO-CERAMICZNYCH PRZEZNACZONYCH NA ELEMENTY LOTNICZE

W pracy przedstawiono wpływ struktury przestrzennej prekursora węgla szklistego na strukturę i właściwości kompozytów zawierających węgiel szklisty pełniący rolę smaru stałego. Opisano wyniki badań porównawczych kompozytów zawierających konwencjonalną piankę węglową oraz kompozytów zawierających pianki z węgla szklistego, otrzymanego z różnych rodzajów prekursorów węgla szklistego w postaci pianki, która stanowiła umocnienie i smar stały. Użycie dwóch różnych faz umacniających związanych z rodzajem zastosowanych prekursorów skutkuje wytworzeniem kompozytów o różnej strukturze i różnych właściwościach. Wymaga też zmiany ciśnienia infiltracji prekursora stosownie do jego wytrzymałości na ściskanie. Pianki pozwalają wprowadzać do struktury kompozytu smary stałe, np. węgiel szklisty, co zmienia w istotny sposób właściwości tribologiczne kompozytów. Na Politechnice Śląskiej opracowano nową metodę wytwarzania kompozytów zawierających węgiel szklisty jako smar stały. Polega ona na wytworzeniu z wybranego prekursora szkieletu przestrzennego z węgla szklistego pochodzącego z różnych rodzajów materiałów zawierających węgiel i infiltracji tego szkieletu ciekłym materiałem osnowy. Materiał użyty do wytwarzania prekursora węgla i parametry procesu jego pirolizy pozwalają w istotny sposób kształtować strukturę i właściwości użytkowe wytwarzanego kompozytu. W artykule opisano wpływ rodzaju prekursora na strukturę i właściwości kompozytów metalowych zawierających ceramikę i smar stały.

Słowa kluczowe: kompozyty hybrydowe, struktura, prekursor, węgiel szklisty, 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. Composites are used to manufacture parts such as the fuselage for Boeing 741 and Airbus A350, some parts for ultra light gliders and sport crafts, skeletons for modern versions of Zeppelins, monocoques for Ferrari and Maserati racing cars as well as a variety of subassemblies for average class cars (Opel, Ford). In a number of cars and trains, composite brake discs, pistons, and cylinders find their frequent application. The primary reason for constructors to use composites with metal, engineering

plastics, and a ceramic matrix is their higher strength in comparison with the matrix. The additional advantage is the fact that it is possible to use foams as the reinforcing phase, which reduces the density and mass of vehicles [1, 2]. Foams produced with the method of foamed suspension gelation demonstrate a several times higher compressive strength (5.1 MPa) than foams produced with ceramic slip deposition on a foamed polymer target [3]. The apparent density of the Al₂O₃ foams used in the investigations is 468 kg/m³. This fact seems essential in the case of air transport. Composites with ceramic foam are perfect materials for the produc-

tion of strengthening parts for fuselages and wings where compressive strength is critical. Ceramic foams increase the compressive strength of composites with an aluminium alloy matrix. Foams with both Al_2O_3 and SiC, as well as glassy carbon reduce the heat flow through the composite, therefore they can additionally function as insulators in airplanes, improving heat economy and reducing fuel consumption. The thermal conductivity of glassy carbon foams is $\lambda = 0.033 \div 0.05 \text{ W}/(\text{mK})^{-1}$. Foams allow the introduction of solid lubricants, e.g. glassy carbon into the composite structure, which significantly changes their tribological properties.

There are numerous methods of introducing solid lubricants into metal matrix composites. The methods applied so far can be divided into two groups i.e.:

- introduction of solid lubricant into matrix material with mixing method,
- introduction of precursor as lubricant into a foam preform and its pyrolysis.

The first method produces a non-uniform distribution of the reinforcing phase and increases the energy costs of mixing and the cost of stirrers. The second method mentioned does not require mixing since the precursor containing the carbon element is in the liquid form. Coating the preform with the liquid precursor ensures uniform distribution of the solid lubricant within the entire volume of the composite which is also conditioned by the more or less regular structure of the preform.

The Silesian University of Technology is the place where a new production method of composites with glassy carbon, functioning as the reinforcement and solid lubricant has been elaborated. The foamy form is produced from a selected glassy carbon precursor and then infiltrated with liquid matrix material. The material used for the carbon precursor and its pyrolysis process parameters enables one to modify the properties of the produced composite. To what extent and how the type of precursor affects the structure and properties of metal composites containing ceramics and solid lubricant, has been described in the article.

PRECURSOR FUNCTIONS IN COMPOSITE

The basic function of a carbon precursor in a composite is the supply of carbon atoms and their distribution to ensure uniform distribution of glassy carbon functioning as a solid lubricant. The carbon distribution should provide the possibility of infiltration with a liquid matrix material. A precursor should possess such a compressive strength which would protect the spatial structure of the lubricant against any damage during pressure infiltration with the matrix material. There should be no sign of conglomerates in the spatial structure of the precursor which would hinder liquid matrix penetration. At the places of conglomerates, voids not filled up with the matrix might occur which could result

in inferior composite properties. The best solution is a precursor in a solid state forming a preform with a required porosity and compressive strength. The porosity of the preform should ensure the required volume fraction of the reinforcing phase and solid liquid. Most frequently, due to technological and economic reasons, composites containing a 10 to 20% ceramic reinforcing phase are used for the production of subassemblies in the transport industry (brake disks are the exception here).

Pistons and cylinders for combustion engines are made of composites with a silumin matrix containing 10% Al_2O_3 fibers. Therefore the preform porosity should amount to 90%. This poses strict requisitions as to the shape of components for the precursor skeleton.

PREFORM FORMING METHODS

The so far suggested solutions [4, 5] were applied for the production of preforms from ceramic foams (Fig. 1). A liquid carbon precursor in an appropriate amount was introduced into the preform, dried and subjected to pyrolysis. The compressive strength, in the case of the preform prepared in this mode, depended mainly on the properties of the foams used. These foams with their porous spheres enable gravitational introduction of the precursor, assure stability of the preform during pressure infiltration with the matrix alloy, and increase the compressive strength of the composite.

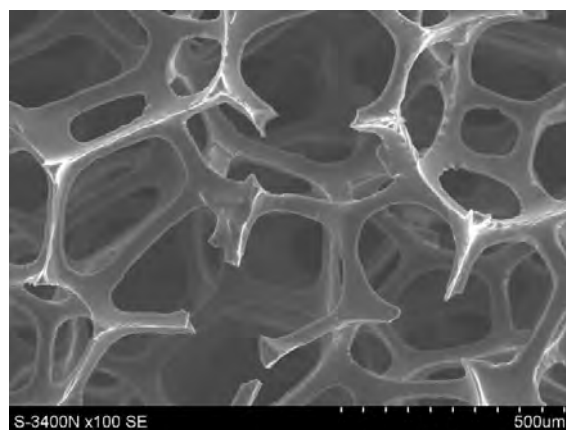


Fig. 1. Spatial skeleton produced from reticulated vitreous carbon (RVC)
Rys. 1. Szkielet przestrzenny wykonany z węgla szklistego (RVC)

More recent solutions elaborated by the authors using carbon foams (Figs. 2b, 3b) do not need the assistance of reinforcing foams. Such skeletons can be made of materials containing carbon e.g., polymer foams or foams from cellulose precursors (felts, mats). Such products are subjected to pyrolysis which ensures transformation of the initial polymer structure into glassy carbon with appropriate tribological properties. The materials from the carbon foams used for glassy carbon thermal insulation (Fig. 1) subjected to high tempera-

ture treatment above 2400°C are available on the market now. Such foams have been used for the experiments.

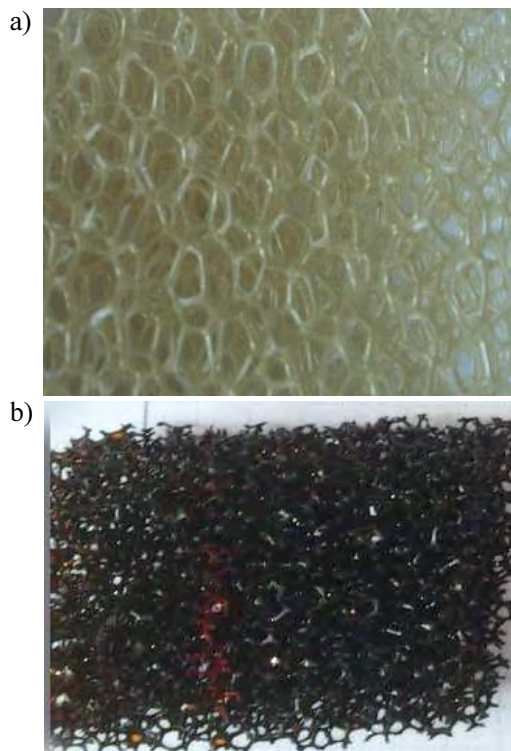


Fig. 2. Carbon precursor in form of polyurethane foam before (a) and after infiltration with resin (b)

Rys. 2. Prekursor węgla w postaci pianki poliuretanowej przed (a) i po infiltracji żywicą (b)

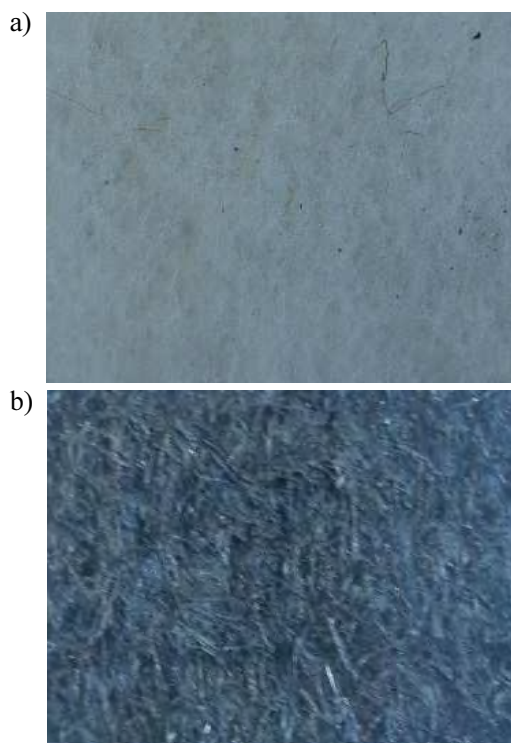


Fig. 3. Felt as carbon precursor before (a) and after infiltration with resin (b)

Rys. 3. Prekursor w postaci filcu z włókien lnianych przed (a) i po infiltracji żywicą (b)

The investigation results on porosity, density, and changes in the dimensions of the initial materials after carbonization proved that the initial porosity of the precursors applied decreased by 10%. The initial dimensions of the precursors were slightly reduced as well i.e., by ca. 6÷10%. Their resin coating guaranteed the existence of the initial carbon structure with a high porosity of about 80%. Such porosity should provide the possibility of liquid metal infiltration into the skeleton structure of the reinforcement. The coating of the initial precursor with resin did not result in significant changes in the structure of the glassy carbon (Fig. 4).

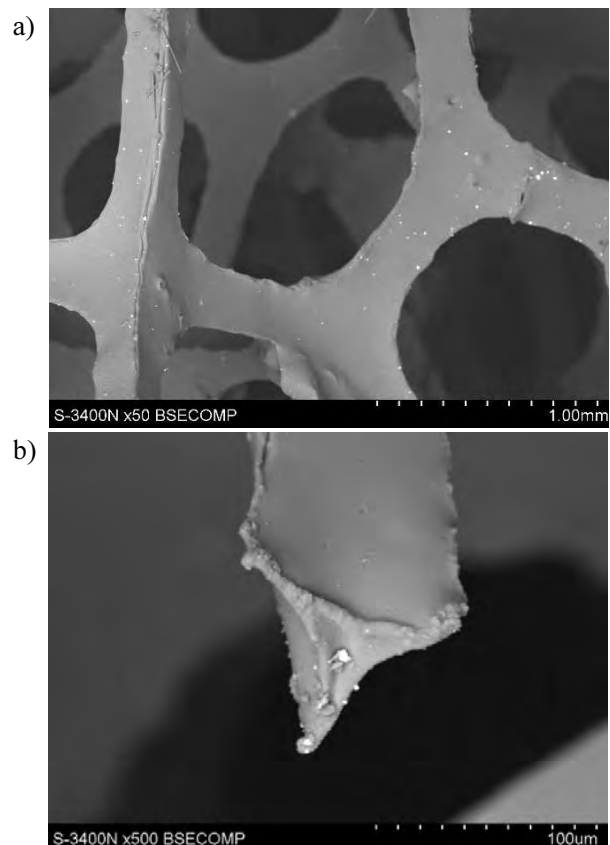


Fig. 4. Microstructure of carbon skeleton from polyurethane foam (a) and morphology of cell wall fracture after pyrolysis (b)

Rys. 4. Mikrostruktura szkieletu węglowego z pianki poliuretanowej (a) i morfologia przełomu ścianki komórki po pirolizie (b)

Porous structures obtained from polyurethanes, polyvinylchloride, and organic fibers have been chosen as the carbonization materials - felt and mat made of flax fibers. These structures were subjected to infiltration with phenol resin in order to retain the initial porosity of the materials applied. The structures were prepared for the carbonization process at temperatures of ca. 1000°C. Figures 2 and 3 present examples of blanks and structures infiltrated with resin.

The paper presents only the results related to the obtained skeletal structures from glassy carbon (Figs. 5 and 6) produced from polyurethane foams. The skeletons presented show a cellular structure where separate cells were formed from thin edges. In the case of some

cells with high porosity (Fig. 6) it is possible to observe wall portions filled with glassy carbon. These filled fragments are attributed to the high viscosity of the resin which is left over between the cell walls. The fillings should not affect the composite production process since they do not close the entire walls of each cell sphere.

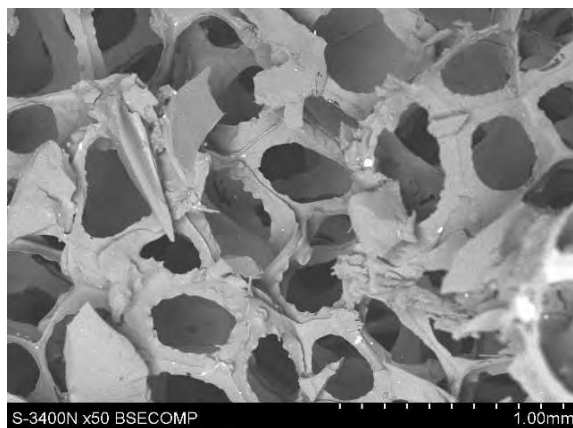


Fig. 5. Microstructure of carbon skeleton from polyurethane foam with porosity of 75%

Rys. 5. Mikrostruktura szkieletu węglowego z pianki poliuretanowej o porowatości 75%

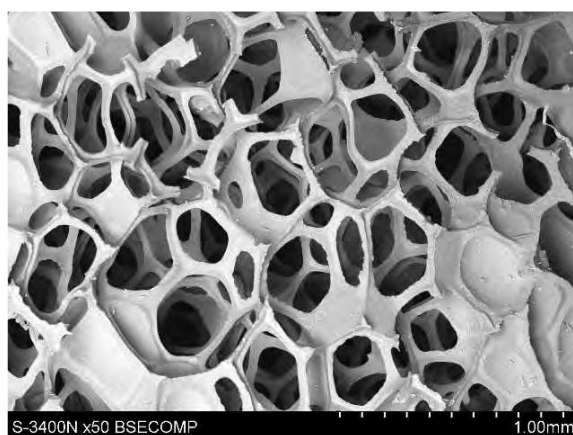


Fig. 6. Microstructure of carbon skeleton from polyurethane foam with porosity of 85%

Rys. 6. Mikrostruktura szkieletu węglowego z pianki poliuretanowej o porowatości 85%

COMPOSITES WITH DIFFERENT PRECURSORS

To be able to define the quality of the obtained skeletal structures produced from different precursors, the authors made an attempt to manufacture a composite containing a carbon skeleton. Composite samples containing the obtained carbon skeleton with a porosity of 85% which functioned as the reinforcing phase were made. Simultaneously, another composite containing commercial Reynolds carbon foam RVC [6] was produced for the reasons of comparison. All the samples were obtained with the method of pressure infiltration with an AlCu3Mg1 alloy in a Degussa vacuum press, in graphite moulds with induction heating. Infiltration was

carried out at the temperature of 740°C and infiltration pressure of 3 MPa due to the relatively low value of compressive strength of the RCV carbon skeleton (acc. to producer $R_c = 0.5$ MPa). Figures 7 and 8 present the micrographic images of the structures.

The use of different glassy carbon precursors can exert a significant influence upon the structure and properties of the produced composites [7]. Selected differences in the structure of glassy carbon composites with a polymer precursor and commercial carbon RVC foam are presented in Figures 7 and 8.

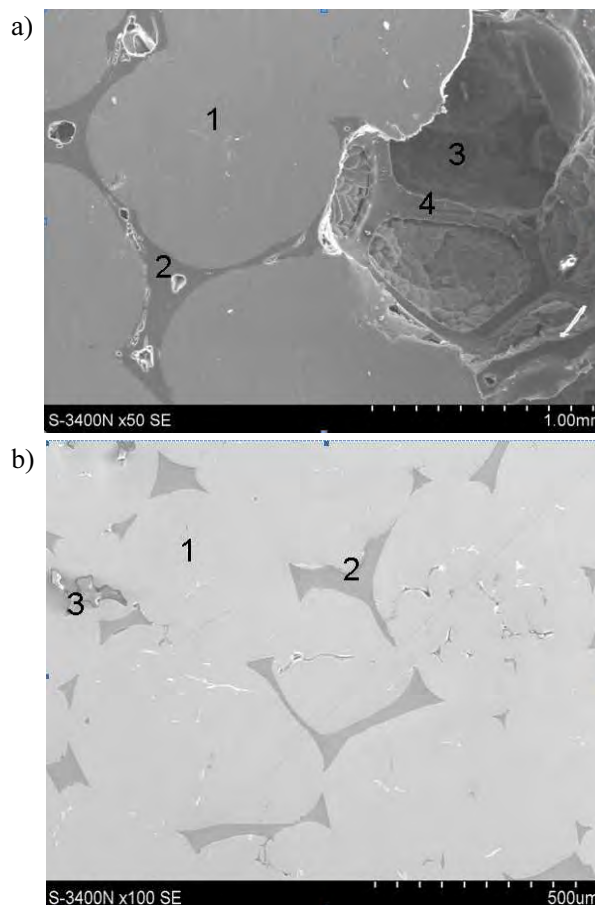


Fig. 7. Microstructure of composite made of RVC-carbon foam (a) and carbon foam with porosity of 85% (b): 1 - matrix, 2 - carbon foam, 3 - carbon cell not filled with matrix material, 4 - crumbled walls of carbon cell

Rys. 7. Mikrostruktura kompozytu wykonanego z pianki węglowej RVC (a) i pianki węglowej o porowatości 85% (b): 1 - osnowa, 2 - pianka węglowa, 3 - komórka węglowa niewypełniona materiałem osnowy, 4 - wykruszone ścianki komórki węglowej

During infiltration of the carbon foam RVC with the matrix metal, even the slightest metal pressure can cause its damage. As Figure 8 shows, a very gentle, open-work foam structure can be damaged as a result of metal penetration. It is clearly visible in the upper part of the samples where liquid metal infiltration starts. Most probably it is caused by high surface tension on the carbon-metal boundary. Damage of the foam structure, displacement of its separated fragments, and even pores formation and casting discontinuities in

the composite can be observed within this area (upper part in Fig. 8).

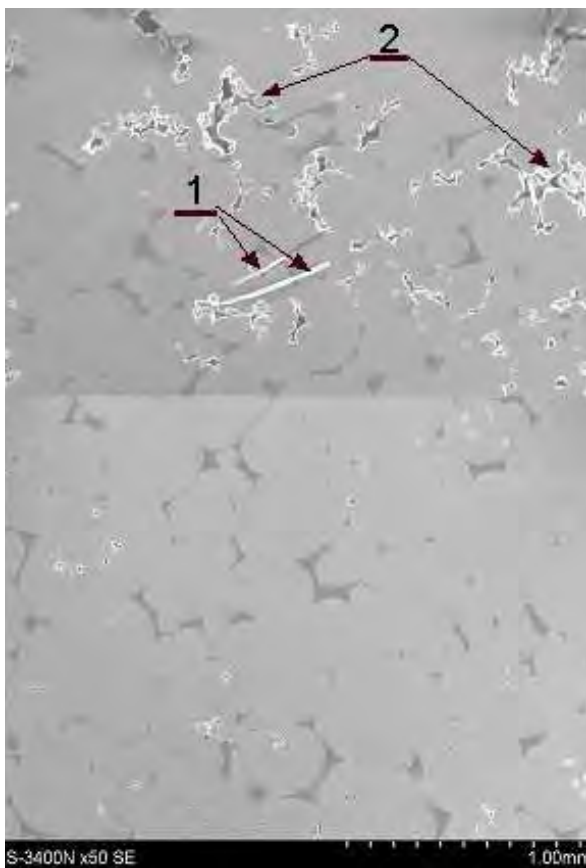


Fig. 8. Changes in microstructure in composite containing RVC carbon foam of different thickness; 1 - foam fragments, 2 - pores and discontinuities

Rys. 8. Zmiana mikrostruktury kompozytu zawierającego piankę węglową RVC na różnej grubości: 1 - fragmenty pianki, 2 - pory i nieciągłości

Such behavior might result from the very low compressive resistance of carbon foam. Infiltration pressure $p = 3$ MPa caused local destruction of the foam. This phenomenon is almost imperceptible in the low and middle part of the samples where metal fills up the voids formed by the carbon skeleton. Matrix areas which form spheres separated by thin carbon structures can be seen. The matrix liquid metal wets the carbon structure thoroughly, filling up areas of closely situated fragments of spheres thus assuring adequate connections on the phase boundary between the metal and reinforcement.

Not so large pores and casting voids are mainly located in the middle of a carbon sphere filled up with metal (3 in Figs. 9 and 10). They should be treated as the effect of contraction of the solidifying matrix metal, and not as a lack of wetting.

In the foam produced from polyurethane, the areas with damage within the sphere edges are much smaller (4 in Figs. 9 and 10). This is a result of increased thickness of the polyurethane cell wall after the resin coating had been performed, which means an increased glassy

carbon thickness and wall strength. Matrix metal fills up the carbon skeleton assuring proper connection at the components boundary (Fig. 10). Closed cell walls did not restrict the liquid metal infiltration process (Fig. 9). In such a skeleton, it would be possible to apply a higher infiltration pressure thus assuring the production of high quality composites.

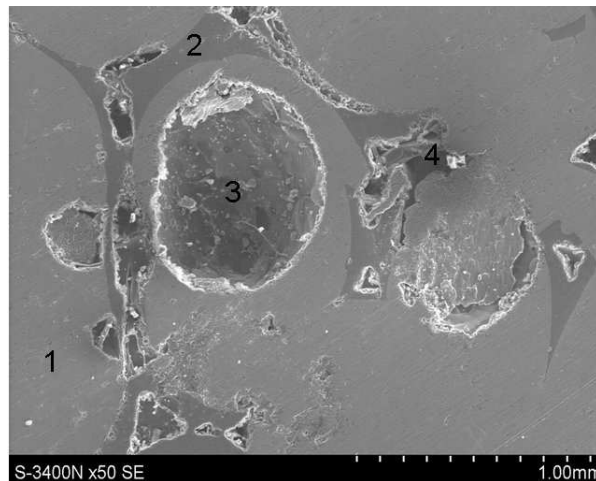


Fig. 9. Microstructure of composite containing carbon foam from polyurethane precursor with 85% porosity

Rys. 9. Mikrostruktura kompozytu zawierającego piankę węglową z poliuretanowego prekursora o porowatości 85%



Fig. 10. Phase boundary in composite containing carbon foam with porosity of 85%: 1 - matrix, 2 - carbon foam wall, 3 - carbon cell not filled up with matrix material, 4 - discontinuity on phase boundary

Rys. 10. Granica rozdziálu faz w kompozycie z pianką węglową o porowatości 85%: 1 - osnowa, 2 - ścianka pianki węglowej, 3 - komórka węglowa niezapełniona materiałem osnowy, 4 - nieciągłość na granicy faz

CONCLUSIONS

The application of precursors made of different materials and with different spatial structure affects the properties of the manufactured composites. The use of various types of preforms decreases the density and thermal conductivity, increases compressive strength and assures uniform distribution of glassy carbon within

the entire volume of the composite. This is of crucial importance when these materials are used for machine parts working in sliding contacts as well as in the case of airplane fuselage elements improving their thermal economy. The presence of thin films of glassy carbon on the surfaces of ceramic spheres decreases friction and wear intensity.

The use of glassy carbon foams provide uniform distribution of the solid lubricant within the entire volume of a composite depending on the structure of the applied precursor. If the skeleton contains local conglomerates which prevent matrix material penetration, local voids are formed inside the composite and negatively affect its properties. If the precursor used shows poor values of permissible pressures, then local destruction of the skeleton might occur during infiltration which would result in destruction of the structure and in undesirable distribution of the solid lubricant in the composite.

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