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DESIGNING CYLINDER LINERS MADE FROM HYBRID COMPOSITES CONTAINING SOLID LUBRICANTS

The paper presents the basic knowledge for designing cylinder sleeves made of hybrid composites containing solid lubricants. The matrix for the described composites could be aluminium wrought alloys used for manufacturing pistons, for example AlCu4Ni2Mg or cast aluminium-silicon alloys used for blocks and cylinder sleeves for engines and compressors, for example AlSi12NiCuMg. These composites should contain two kinds of reinforcing phase, i.e. strengthening Al_2O_3 or SiC foam and thin layers of glassy carbon. Ceramic foam increases the compressive strength and wear resistance of the composite and decreases the thermal conductivity. Glassy carbon plays the role of a solid lubricant. A cylinder sleeve manufactured of a composite containing particles or spheres of aluminium oxide will possess other properties than one made of a composite containing silicon carbide. The reason for that is the different thermal conductivity for Al_2O_3 ($\lambda = 20 \div 30$ W/(mK)) and SiC ($\lambda = 100 \div 130$ W/(mK)). Cylinder sleeves manufactured of a composite containing ceramic foams (Al_2O_3 or SiC) will possess a similar, but much lower thermal conductivity (for Al_2O_3 foam $\lambda = 0.2$ W/(mK) and SiC foam $\lambda = 0.12$ W/(mK) at temperatures of 20÷200°C. It is very important for air compressors in which the piston rings are manufactured of composite plastics.

Keywords: cylinder liner, solid lubricant, hybrid composite, ceramic foam, thermal conductivity

PROJEKTOWANIE TULEI CYLINDROWYCH Z KOMPOZYTÓW HYBRYDOWYCH ZAWIERAJĄCYCH SMARY STAŁE

Przedstawiono podstawy projektowania tulei cylindrowych z kompozytów hybrydowych zawierających smary stałe. Osnową opisanych kompozytów mogą być stopy aluminium do przeróbki plastycznej stosowane na tłoki, np. AlCu4Ni2Mg, lub odlewnicze stopy aluminium z krzemem stosowane na kadłuby i tuleje cylindrowe silników i sprężarek tłokowych, np. AlSi12NiCuMg. Osnowę kompozytów na cylindry siłowników mogą stanowić stopy aluminium z magnezem. Kompozyty te powinny zawierać dwa rodzaje fazy zbrojącej, tj. umacniającą piankę z tlenku aluminium lub węglika krzemu oraz cienkie warstewki węgla szklistego. Pianka ceramiczna zwiększa wytrzymałość na ściskanie i odporność na zużycie kompozytu oraz zmniejsza przewodność cieplną, a węgiel szklisty pełni rolę smaru stałego. Tuleja cylindrowa wykonana z kompozytu zawierającego cząstki lub sfery z tlenku aluminium będzie miała inne właściwości cieplne niż zawierająca cząstki SiC, ze względu na mniejszy współczynnik przewodności cieplnej ($\lambda = 20 \div 30$ W/(mK)) dla Al_2O_3) niż tuleja zawierająca węglik krzemu ($\lambda = 100 \div 130$ W/(mK)). Tuleje wykonane z kompozytu z osnową siluminową zawierającego cząstki z SiC będą miały lepszą stabilność wymiarową, ponieważ przewodność cieplna materiału osnowy jest zbliżona do przewodności cieplnej SiC. Tuleje cylindrowe wykonane z kompozytu zawierającego pianki z tlenku aluminium lub węglika krzemu będą miały zbliżoną przewodność cieplną, jednak znacznie mniejszą niż tuleja zawierająca cząstki, ponieważ przewodność cieplna pianki Al_2O_3 wynosi $\lambda = 0,2$ W/(mK), a SiC $\lambda = 0,12$ W/(mK) w temperaturze 20÷200°C. Jest to bardzo istotne w sprężarkach powietrza, w których pierścienie tłokowe są wykonane z kompozytowych tworzyw sztucznych.

Słowa kluczowe: tuleje cylindrowe, smary stałe, kompozyty hybrydowe, pianka ceramiczna, przewodność cieplna

INTRODUCTION

The tribological properties of sliding contacts during the operation of machine parts and equipment can be predicted as early as at the design stage. Previous experience in the field of materials science, tribology and ecology shows that when selecting materials for the contacts, one should take into account the following requirements [1, 2]:

1) The materials for the contacts should be adjusted to the operating conditions of the particular pair.
2) The rubbing materials should not be prone to adhesive tacking, so-called dissimilar materials.
3) The hardness of one of the materials, usually the part replacement is easier and cheaper, should be about 20 units lower than the hardness of the other material.

4) For the contact, one should select a material with a low shear strength, which will reduce the friction forces and operating costs, as well as the impact of the used lubricants on the environment.
5) In the contact, one should apply a material of the highest hardness.

Properties resulting from the high operating temperature, i.e.:

- high thermal conductivity,
- low thermal expansion

should be added to the requirements specified in item 1 above imposed on materials for pistons and cylinder sleeves of piston thermal machines.

These requirements can be met by a composite material containing two kinds of reinforcing phase. One of them may be for example very hard particles, spheres, fibers, or less hard ceramic foams and glassy carbon with a low shear strength (30÷50 MPa) acting as a solid lubricant. The working conditions of piston groups operating in combustion engines and piston compressors are met by composites based on aluminum alloys because they are characterised by a lower density than iron alloys, better thermal conductivity and corrosion resistance, including resistance to sulfur. This paper is devoted to the design of cylinder sleeves for piston machines, taking into account the above-mentioned requirements.

DESIGNING A CYLINDER SLEEVE

The operating conditions of cylinder sleeves applied in piston machines define the properties of the selected materials. The cylinder sleeve works under a pulsating pressure that causes fatigue bending (the average and indicated instantaneous pressure in engines, extrusion pressure in compressors and working pressure in actuators). The operating temperatures of cylinder sleeves used in combustion engines range between 120°C under the piston and 200°C in the combustion chamber. Part of the combustion chamber comes into contact with exhaust gases containing environmentally harmful components, e.g. NO_x or SO_2. The working surfaces of the engine sleeves are lubricated by splashing engine oil. When starting a cold engine, the oil viscosity is too high and the lubrication is ineffective. The wear of the engine sleeve during a cold start is comparable to wear occurring for two hours in a steady thermodynamic state. Therefore, when designing cylinder sleeves one should allow for an additional solid lubricant in the friction zone. Materials engineering offers many opportunities to ensure such a solution. Based on the previous experience of the authors [3-5] this solution could take the form of a cylinder sleeve made of a hybrid composite containing spheres or fibers and ceramic foam as the strengthening phase, as well as glassy carbon as the solid lubricant. In addition, glassy carbon can support the process of purifying exhaust gases because it can reduce certain environmentally harmful components [6]. This results from the high resistance to oxidation at elevated temperatures, which is many times higher than that of other forms of carbon, e.g. pyrolytic graphite. Ceramic foams coated with glassy carbon are characterized by a large specific surface area and high porosity allowing one to obtain a high degree of conversion per volume unit [7].

When designing cylinder sleeves, one can choose ceramic foams or fibers made of two materials, e.g. Al_2O_3 and SiC. Their different characteristics have been listed in Table 1.

TABLE 1. **Comparison of selected Al_2O_3 i SiC properties**
TABELA 1. **Porównanie wybranych właściwości Al_2O_3 i SiC [7-9]**

Property	Al_2O_3, 99.8%	SiC
Density [kg/m^3]	3960	3100
Thermal conductivity coefficient λ [W/(mK)]	30 - bulk or 0.20 foam	100÷170 - bulk or 0.12 foam
Compressive strength Rc [MPa]	4000	2000
Thermal expansion coefficient α 20÷400°Cx10^{-6}K^{-1}]	7.5	3.5
Bending strength R_g [MPa]	500	350
Vickers hardness [GPa]	18	25
Maximal employing temperature [°C]	1500	1800
Possibility of obtaining open porosity	90%	80÷90%

Table 1 shows that a composite containing Al_2O_3 particles is characterised by definitely worse conditions of carrying away heat than a composite containing SiC particles, due to its thermal conductivity. The application of Al_2O_3 and SiC foams results in a dramatic reduction in the thermal conductivity, the values of which are similar for both materials. The fitting clearance of a sleeve containing Al_2O_3 has to be greater than of one containing SiC because the thermal expansion of the silicon carbide is two time less than that of the aluminum oxide for solid materials. The thermal stresses in a composite containing SiC particles will be smaller due to the thermal expansion coefficient. The wear resistance of a composite containing SiC particles will be higher due to their higher hardness. The calculated friction coefficient of the composite containing SiC, based on the hypothesis by Ernst and Merchand, will be lower because of the higher hardness of silicon carbide.

Making a cylinder sleeve with a local composite insert should not pose any technological problems because the ceramic foam may be produced as a separate preform (Fig. 1a) of the required dimensions, and from fibers one can prepare a similar preform by combining the fibers with the use of a decomposable aperture during the composite formation process (Fig. 1a). The produced preforms are coated with a layer of liquid carbon precursor and subjected to a pyrolysis process in protective atmosphere (Fig. 1c). Then, the preform is placed in a mold and infiltrated with a liquid matrix alloy (Fig. 1d). Figure 1 presents a model of a cylinder sleeve made of aluminum alloy with a local composite insert made of various materials.

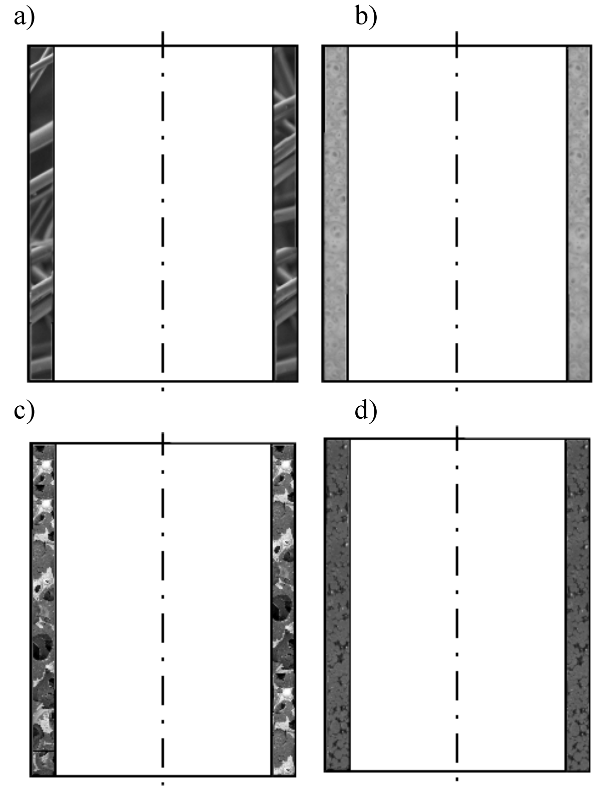

Fig. 1. Model of cylinder liner insert made of hybrid composite containing Al_2O_3 foam and glassy carbon

Rys. 1. Model wkładki tulei cylindrowej wykonanej z hybrydowego kompozytu zawierającego piankę Al_2O_3 i węgiel szklisty

Figure 2 shows the microstructure of the contact of a cast-iron piston ring (2) and a piston silumine coat with a composite cylinder sleeve made of AlMg5 alloy reinforced with Al_2O_3 foam and coated with a glassy carbon layer (3a and 3b).

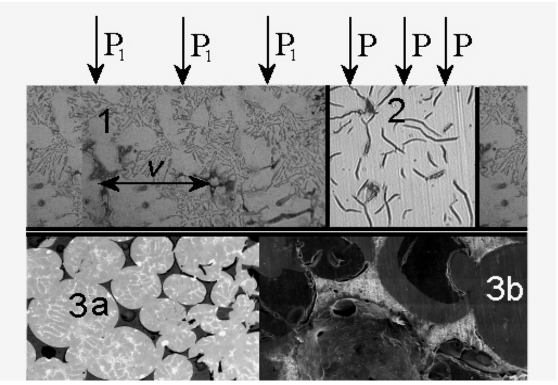

Fig. 2. Model of cast-iron piston ring/piston skirt-composite cylinder sleeve: 1 - piston skirt from AC 47000 alloy, 2 - piston ring from GJL 300, 3 - composite cylinder sleeve made of AlMg5 alloy with composite insert reinforced with Al_2O_3 foam coated with glassy carbon

Rys. 2. Model skojarzenia żeliwny pierścień tokowy/płaszcz tłoka-kompozytowa tuleja cylindrowa: 1 - płaszcz tłoka ze stopu AC 47000, 2 - pierścień tłokowy z GJL 300, 3 - kompozytowa tuleja cylindrowa ze stopu AC AlMg5 z wstawką z kompozytu zbrojonego pianką Al_2O_3 pokrytą węglem szklistym

The foam strengthens the matrix material (composite *Rc* is almost 4 times higher than matrix *Rc* [5]), and the glassy carbon acts as a solid lubricant in the event of a short-term oil shortage. During sliding between the cast-iron piston ring and the composite sleeve (3a), glassy carbon and graphite wear products are brought from the cast iron up to the surface of both the composite (3b) and the cast iron. The pearlitic matrix of the ring slides on the ceramic foam of the composite, ensuring high hardness in the pair (meeting 3rd and 5th requirement), and the oil layer present in between them ensures a very low, depending on the oil viscosity, shear strength (meeting 4th requirement), which significantly reduces the friction coefficient. With a shortage of oil, the rubbing surfaces are coated with graphite and glassy carbon wear products characterised by a low shear strength, which guarantees boundary friction throughout the cooperation because the glassy carbon located evenly within the entire composite insert is not completely removed. A similar model can be built for the contact of a composite plastic piston ring-composite cylinder in an air compressor or pneumatic actuator. The wear debris of glassy carbon and plastic will be deposited on the sliding surfaces, reducing the friction forces and wear.

The thermal conductivity coefficient of the material of the composite cylinder sleeve could be calculated using the results from the mixtures rule dependence:

$$\frac{1}{\lambda_k} = \frac{V_o}{\lambda_o} + \frac{V_{cf}}{\lambda_{cf}} + \frac{V_{gc}}{\lambda_{gc}} \tag{1}$$

where:

λ_k - composite thermal conductivity coefficient, W/(mK),
λ_O - matrix thermal conductivity coefficient, for silumine $\lambda = 160$ W/(mK),
λ_{cf} - ceramic foam thermal conductivity coefficient, for Al_2O_3 foam $\lambda = 0.2$ W/(mK), for SiC foam $\lambda = 0.12$ W/(mK) at 20÷200°C,
λ_{gc} - glassy carbon thermal conductivity coefficient, $\lambda = 6.3$ W/(mK) at 20°C,
V_o - matrix volumetric fraction, 88% AlSi12CuNi alloy,
V_{cf} - ceramic foam volumetric fraction, 10%,
V_{gc} - volumetric fraction of glassy carbon, 2%.

After inserting the volume fraction values $V_o = 0.9$, $V_{cf} = 0.08$ and $V_{gc} = 0.02$ and the thermal conductivity values of the matrix (160), ceramic foam (0.2) and glassy carbon (6.3), we obtain the approximate thermal conductivity coefficient value for the composite $\lambda_k = 2.44$ W/(mK). The thermal conductivity coefficient value for a composite containing SiC foam amounts to $\lambda = 1.15$ W/(mK).

VERIFICATION OF DESIGNED MODEL

The heat generated during friction is carried away by both the ring and the cylinder sleeve. During engine operation, the heat flow originating from combustion is much greater than that coming from friction. During the operation of an oil-free piston compressor or pneumatic actuator, the friction heat has a much greater impact on the friction and wear. In order to examine the effect of the reinforcing phase on the friction force and heat conduction values, tribological tests in air on three contacts have been conducted. The sample was made of a cast iron (GLJ-250) pin and the countersample was disks made of an AlMg5 alloy matrix, of a composite containing Al_2O_3 foam only and of a composite containing foam coated with glassy carbon. In the pin, four holes every 1.5 mm from the sliding surface were made in which thermocouples were placed. Figure 3 shows a friction contact with fixed thermocouples.

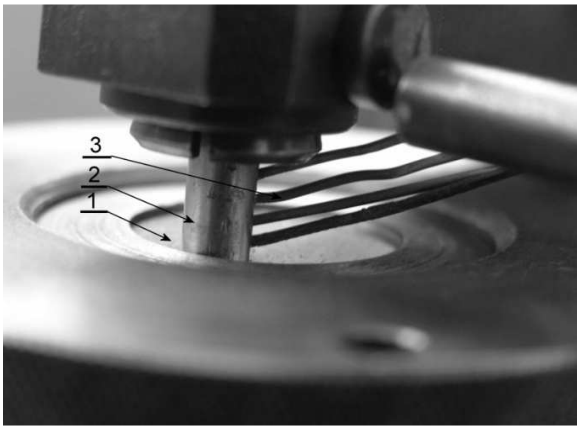

Fig. 3. View of friction contact with thermoelements: 1 - composite disc, 2 - GJL-200 pin, 3 - thermoelements

Rys. 3. Widok węzła tarcia z termoparami: 1 - kompozytowa tarcza, 2 - trzpień GJL-200, 3 - termopary

The results are summarized in Table 2 and Figures 4-5. The given temperatures are the values after 30 minutes of sliding, i.e. after stabilization of the friction coefficient. The friction coefficient values relate to the beginning and end of sliding.

TABLE 2. **Temperature in cast iron pin vs. distance from friction surface and friction coefficient (μ) during sliding against selected materials**

TABELA 2. **Temperatura w trzpieniu żeliwnym w funkcji odległości od powierzchni tarcia i współczynnik tarcia (μ) podczas współpracy z badanymi materiałami**

Temperature [°C]	**1.5 mm**	**3.0 mm**	**4.5 mm**	**6.0 mm**	μ
Matrix	52	44	42	42	0.35÷0.76
Matrix+Al_2O_{3F}	68	58	54	52	0.4÷0.58
Matrix+Al_2O_{3F} +GC	66	64	58	48	0.32÷0.48

Figure 4 presents a sample dependence of the friction coefficient in the GJL-200/composite containing Al_2O_3 foam coated with glassy carbon contact versus sliding time. The chart shows the friction force oscillation during rubbing. Only the oscillation of the friction forces in the contact of the matrix material and composite containing Al_2O_3 foam were higher (Table 1).

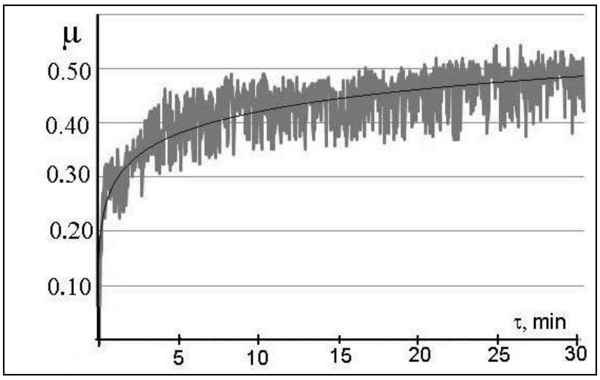

Fig. 4. Friction coefficient vs. sliding time in contact GJL-200/composite containing Al_2O_3 foam coated with glassy carbon (p = 2 MPa, v = 0,5 m/s, friction in air)

Rys. 4. Współczynnik tarcia w funkcji czasu współpracy w skojarzeniu GJL-200/kompozyt zawierający piankę Al_2O_3 pokrytą węglem szklistym (p = 2 MPa, v = 0.5 m/s, tarcie technicznie suche)

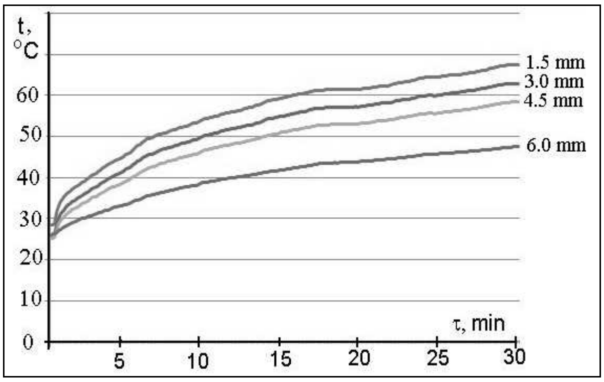

Fig. 5. Temperature in cast iron pin depending on distance from contact surface vs. sliding time

Rys. 5. Temperatura w trzpieniu żeliwnym w odległości od powierzchni tarcia w funkcji czasu współpracy

Figure 5 shows a sample of temperatures in cast iron pin versus sliding time in four measuring points in distance from sliding surface during sliding against composite containing Al_2O_3 foam coated with glassy carbon.

DISCUSSION OF RESULTS AND DEVELOPMENT PERSPECTIVES

The verification tests show that the addition of Al_2O_3 foam to the AlMg5 alloy results in deterioration of the thermal conductivity of that alloy to such an extent that the temperature of the cast-iron pin sliding against the composite increases by 16 degrees in the friction zone - 1.5 mm from the contact surface (Table 2). This confirms the validity of the calculation of the substitute thermal conductivity coefficient, using formula (1). This increase exceeds 6 mm, which in practice means almost the entire thickness of the piston ring. After coating the foam with glassy carbon, this increase is smaller by 2 degrees, which is caused by the lubricating action of the carbon. The friction-induced temperature increase component may be lower because of the similar friction coefficient values of the cast iron on the matrix and on the composite. The addition of glassy carbon decreases the value and deviation of the friction coefficient.

The glassy carbon properties depend on the precursor pyrolysis conditions, including the temperature. Under certain conditions, one can obtain glassy carbon acting as a process catalyst. This may be important for the combustion processes in combustion engines. Because of the presence of glassy carbon on the sliding surface of the cylinder sleeve within the combustion chamber, one can reduce the amount of environmentally harmful substances and slightly increase engine efficiency thanks to the after-burning of exhaust gas components.

Making a foam preform for a cylinder sleeve, the porosity of which is open on the surface only but closed in the middle of the thickness so as to prevent penetration of the liquid carbon precursor and the liquid material of the matrix into the insert, may contribute to a slight decrease in the weight of the cylinder sleeve.

SUMMARY

The proper selection of components for composite materials for cylinder sleeves at the design stage, according to the 5 requirements presented in the introduction, enables one to produce sleeves by adding a solid lubricant, preventing a dangerous engine seizure caused by a temporary shortage of oil, may extend machine durability. However, the presence of a ceramic reinforcing foam reduces the thermal conductivity, which can increase engine efficiency provided that the lubrication system remains efficient.

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