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TRIBOLOGICAL PROPERTIES OF COMPOSITE PISTON RINGS DESIGNED FOR OIL-FREE CONTACTS IN ECOLOGICAL TRANSPORT

WŁAŚCIWOŚCI TRIBOLOGICZNE KOMPOZYTOWYCH PIERŚCIENI TŁOKOWYCH PRZEZNACZONYCH DO BEZOLEJOWYCH SKOJARZEŃ W EKOLOGICZNYM TRANSPORCIE

Key words: means of transport, piston rings, oil-free contact, solid lubricant, transfer film.

Abstract: The paper presents a comparison of tribological properties for two generations of sliding contacts, i.e. TG15/Anodic Hard Coating and PASL/AlMC in oil-free piston compressors designed for ecological transport. In the first contact, the piston ring material is Teflon-graphite TG15 (PTFE+15% graphite), and in the other, an acetal-based (PA) sliding composite (PASL) with additional substances acting as solid lubricants (SL), i.e. PTFE, graphite and carbon fibres. Rings made of plastics slide under conditions of technically dry friction against a cylinder liner's surface made of aluminium alloy and reinforced by an electrolytic oxide coating (AHC) in the case of the first contact and with a cylinder liner surface made of alloy reinforced by the addition of Al_2O_3fibres (AlMC composite) in the latter contact. During friction, the wear debris of the filler form a sliding film (transfer film) on the cylinder liner's surface, which results in a friction coefficient from 0.12 to 0.1 without the use of oil or greases.

Słowa kluczowe: środki transportu, pierścienie tłokowe, skojarzenie bezolejowe, smar stały, film ślizgowy.

Streszczenie: W artykule opisano tribologiczne właściwości tribologiczne dwóch generacji skojarzeń ślizgowych, tj. TG15/anodowa powłoka tlenkowa oraz PASL/AlMC stosowanych w bezolejowych sprężarkach powietrza przeznaczonych do ekologicznego transportu. W pierwszym skojarzeniu materiałem pierścienia tłokowego jest tarfleno-grafit TG15 (PTFE+15% grafitu), a w drugim ślizgowy kompozyt z osnową acetalową (PASL) z dodatkiem substancji pełniących rolę smaru stałego (SL), tj. PTFE, grafit i włókna węglowe. Pierścienie wykonane z tworzywa sztucznego współpracują, w warunkach tarcia technicznie suchego, z gładzią tulei cylindrowej wykonanej ze stopu aluminium umacnianego anodową powloką tlenkową (AHC) w pierwszym skojarzeniu oraz z gładzią tulei wykonanej ze stopu aluminium umacnianego przez dodanie włókien Al_2O_3 (kompozyt AlMC) w drugim skojarzeniu. Podczas tarcia produkty zużycia napełniaczy tworzą na gładzi tulei cylindrowej film ślizgowy (film transferowy), co skutkuje współczynnikiem tarcia 0.12 do 0.1 bez użycia olejów lub smarów.

INTRODUCTION

Specialists have been dealing with the design and application of composite materials in constructing means of transport for many years **[L. 1–2].** By increasing the strength of composites in relation to their matrix (up to 30%), it is possible to reduce the weight of vehicles and fuel consumption, as well as the amount of gases and solid particles they emit. This is particularly important in motor vehicles and air transport, where combustion engines have dominated so far. Composite cylinder sleeves allow combustion engines to run longer (reduced wear), while brake discs allow vehicles to be lighter. The

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weight of a cast-iron brake disc for the passenger car is 5.750 kg, whereas it is 1.875 kg in the case of an AlMC disc with similar dimensions **[L. 2].** The most commonly used in transport are composites with an aluminium alloy matrix, called AlMC (Aluminium Matrix Composite) **[L. 3–5].**

Machines using oils and greases contribute to environmental pollution. Therefore, oil-free contacts made from composites with embedded solid lubricants are frequently used **[L. 2, 6, 7].** In technical means of long-distance transport (door opening, brake booster) and short-distance transport (food and medicine feeders), oil-free contacts, as well as ones without greases, are required. In such contacts, solid lubricants with a low shear strength, which are the third body mentioned later in the paper, are used. Solid lubricants should be incorporated into the sliding machine parts' altering (due to wear) surface layer. Composite plastics, including those containing nanomaterials, are the materials which meet this requirement **[L. 7].**

From an ecological point of view, the sliding partner is important. In industrial praxis, oil-less compressors with a cylinder liner coated by using chemical and electrochemical treatments, for example, hard anodic coating **[L. 8]** and nickel silicon carbide plating Nikasil **[L. 9]** are used. Both technologies are harmful to the environment.

The friction hypothesis developed by Ernst H. and Merchant E. **[L. 10]** claims that the coefficient of friction is a function of material properties of sliding machine parts, which can be expressed as follows:

$$\mu = \frac{\tau}{H} + \mathrm{tg}\alpha \tag{1}$$

τ – shear strength of the resulting tacking junction, calculated from the Clausius-Clapeyron equation, and in practice, the shear strength of the weaker material [MPa]; in composites, it can be used as solid lubricant PFTE, graphite or vitreous carbon,
H – hardness of stronger material [MPa], e.g., anodic hard coating, Al_2O_3fibres,
α – angle of inclination of the real contact surface (roughness peaks).

As a result of the above-mentioned hypothesis, the coefficient of friction can be reduced if two appropriately selected materials, i.e., one with a low shear strength (τ) and the other with high hardness (H), rubbing in the friction zone. The second part of the equation (1) says that the smaller the angle of inclination of surface irregularities (α), the lower the coefficient of friction, and smaller angles have surfaces with lower roughness. It follows from both terms of the equation that in order to reduce the friction coefficient, the machine parts designed for sliding contacts must be made of very hard material with low roughness and soft material, as shear strength and hardness are correlated with tensile strength ($\tau \cong 0.6\ \sigma_m$). A material that meets this requirement can be a hybrid composite containing a very hard reinforcing phase and a solid lubricant with low shear strength.

From the point of view of ecological transport, the aim should be to produce material contacts whose wear is minimal. If we design a contact in which a material with low shear strength slides against material with high hardness, we will expose the former to too intensive abrasive wear. Therefore, a practical solution is a contact containing three materials, i.e., two hard and one very soft, with a low shear strength, between them. A lubricant is such a third material with a very low shear strength. The study will present the possibilities of using composite contacts that do not require oils or greases.

MATERIALS AND METHODS

As part of popularising ecomobility, an oil-free contact has been developed which can slide in air compressors used in technical means of transport. Its usefulness was tested in comparative studies of two oil-free sliding contacts, i.e.:

- Teflon composite/Al alloy coated with an anodic hard coating (TG15/AHC),
- Polyacetal composite/AlSi12NiMg+12% Al_2O_{3F} (PASL/AlMC).

The first contact is used in oil-free air compressors in the braking systems of trucks, and for opening the doors in buses and railroad cars **[L. 8, 11].** The other one was developed to replace the former due to the environmental harmfulness of electrolytic oxidation and the chemical reagents used.

Tests were performed using a tribology tester (**Fig. 1**), whose system imitates the sliding of piston rings against a cylinder sleeve liner. Specimens for testing (cube, a = 10 mm) were cut out of TG15 and PASL, and the counter-specimens (rectangular prism, 6x15x120 mm) were cut out of a AW-6062 alloy coated with 25 µm thick AHC, and of a AC-47000+10% Al_2O_3 composite. The tests were carried out in similar conditions to the work of piston rings in an air compressor (p = 2 MPa): relative average velocity v = 2.5 m/s, unit pressure of piston on a cylinder's liner p = 0.5 MPa, technically dry friction, test time τ = 100 h in four repetitions. During the tests, mass losses of the specimens were measured using analytical scales with an inaccuracy of 0.2 mg, and the friction coefficient was measured with astrain gauge transducer with an accuracy of 3% of the value measured (Spider 4+Catman Easy).

The piston material TG15 contained PTFE+15% of graphite. The matrix of the PASL composite is polyacetal with hardness (80 Shore D, HR = 170 MPa) and strength (Rm = 70 MPa, at 20°C and 25 MPa at 120°C) higher than that of PTFE (Rm = 25–30 MPa) and graphite (Rm = 8–10 MPa), while the solid lubricant was a 15% mixture of PTFE, graphite and carbon fibres (low τ) (**Fig. 2**). This material was developed to slide against hard ceramic materials, e.g., Al_2O_3, as a continuous layer or dispersed fibres.

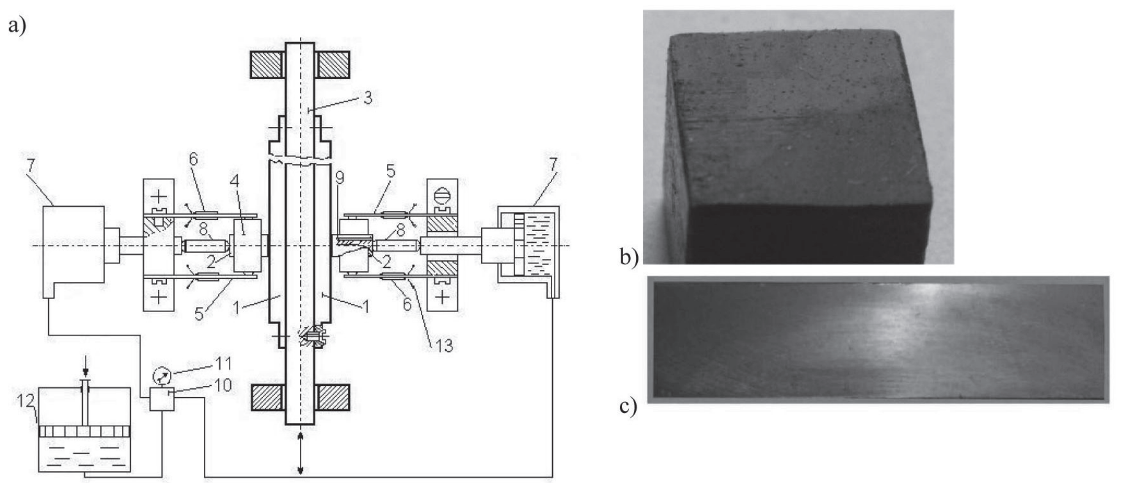


Fig. 1. Scheme of the tribological tester (a) and sample (b) with a counter – sample view (c): 1 – counter – sample (part of cylinder liner), 2 – sample (part of composite piston ring), 3 – slide way, 4 – hinged sample holder, 5 – force sensor, 6 – strain gauge bridge, 7 – hydraulic cylinder, 8 – hinged pusher, 9 – bore for thermocouple, 10 – 4/2 manipulator, 11 – pressure gauge, 12 – hydraulic pump, 13 – exit to Spider 4 with Catman Easy software

Rys. 1. Schemat testera tribologicznego (a) i próbka (b) z przeciwpróbką (c): 1 – przeciwpróbka (wycinek z tulei cylindrowej), 2 – próbka (wycinek z pierścienia tłokowego), 3 – prowadnica, 4 – przegubowy uchwyt próbki, 5 – przetwornik siły, 6 – mostek tensometryczny, 7 – siłownik hydrauliczny, 8 – przegubowy popychacz, 9 – otwór pod termoparę, 10 – rozdzielacz 4/2, 11 – ciśnieniomierz, 12 – pompa hydrauliczna, 13 – wyjście do rejestratora Spider 4 z oprogramowaniem Catman Easy

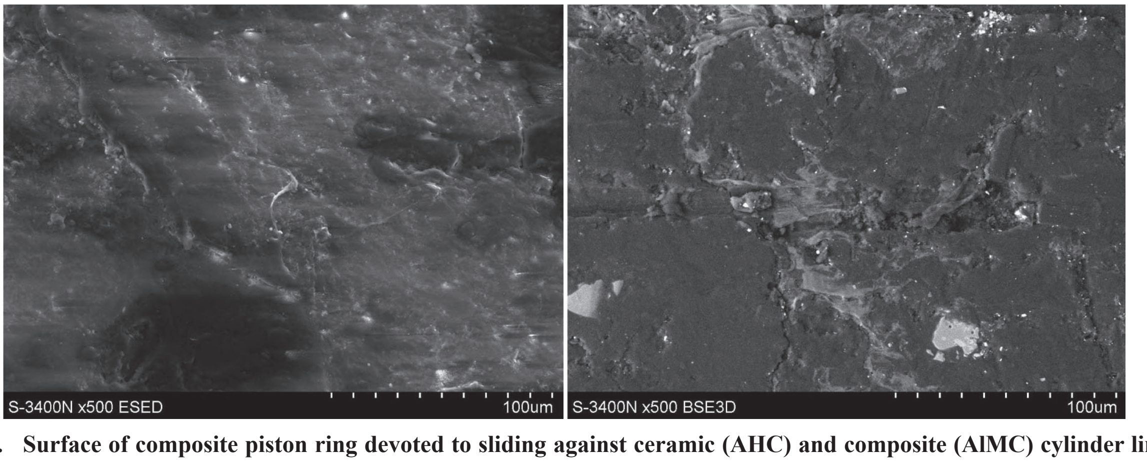


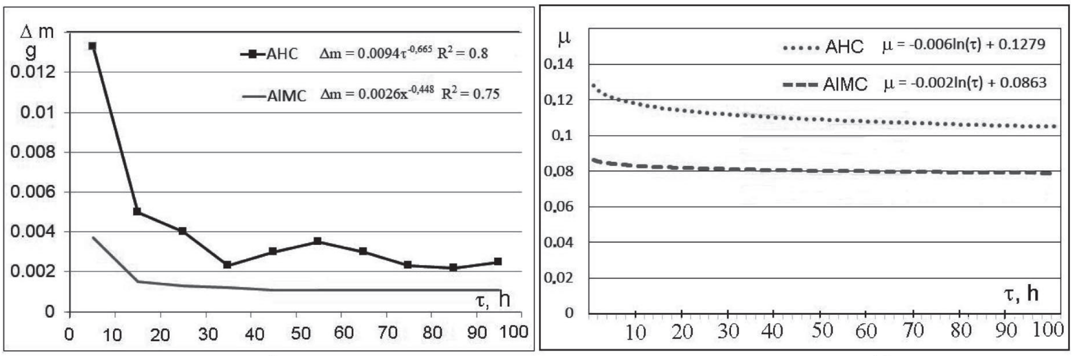
Fig. 2. Surface of composite piston ring devoted to sliding against ceramic (AHC) and composite (AlMC) cylinder liner; SEM: a – before sliding – small groups of PTFE particles as brighter places, b – after sliding against AHC – plastic deformations of matrix and abrasive wear

Rys. 2. Powierzchnia kompozytowego pierścienia tłokowego przeznaczonego do współpracy z ceramiczną powłoką tlenkową (AHC) i z kompozytem (AlMC): a – przed współpracą – widoczne małe zgrupowania cząstek PTFE jako jasne miejsca, b – po współpracy z AHC – widoczne plastyczne odkształcenia osnowy i ślady zużywania ściernego

TEST RESULTS AND DISCUSSION

The results of weight loss and friction coefficient measurements (trend lines) are presented in **Fig. 3**. The specimens, after tribological tests, were subjected to microscopic (**Figs. 2, 4a, 4b, 5**) and macroscopic (**Figs. 4c, 4d**) examinations. In order to determine the thickness of the sliding film, and polished cross-sections of the counter-specimens were made (**Figs. 5–6**), and an analysis of the chemical composition was carried out (**Fig. 7**).

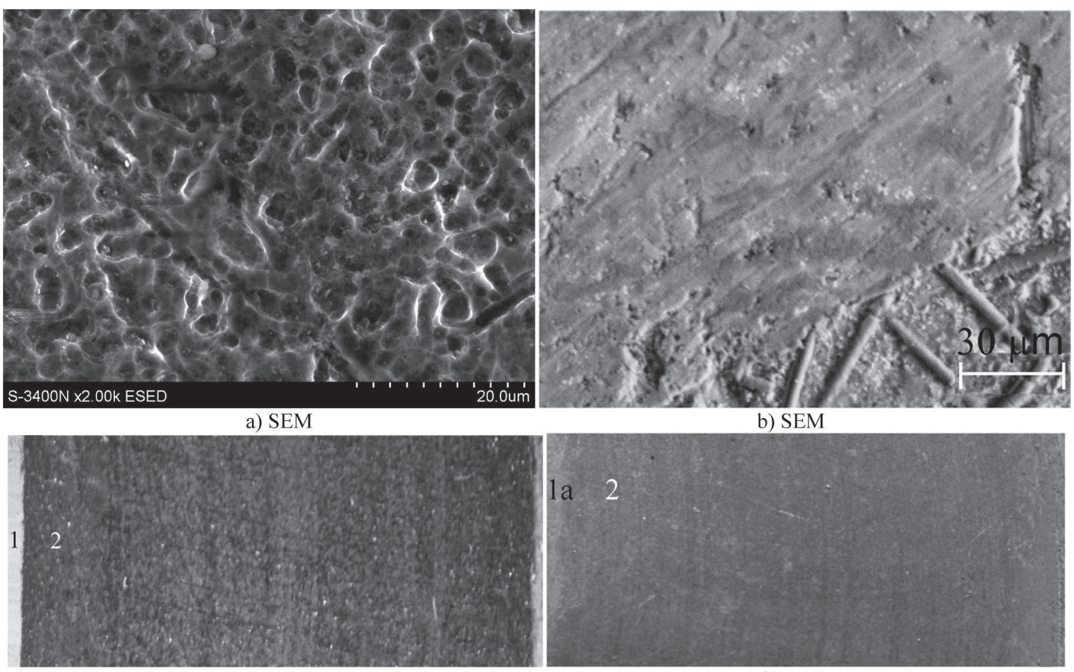
The essence of oil-free plastic material/ceramics contacts is the production of a sliding film on the ceramic's surface during friction. The dominant component of the film is a modifier containing solid lubricants. The AHC surface is appropriately developed (**Fig. 4a**) and shows adhesion to the plastic material.



a) b)

Fig. 3. Mass wear of the piston ring (Δm, a) and friction coefficient (μ, b) vs. sliding time (*τ*) against AHC and AlMC

Rys. 3. Ubytek masy pierścienia tłokowego (Δm, a) i współczynnik tarcia (μ, b) w funkcji czasu współpracy (τ) z AHC i AlMC



a) SEM b) SEM

c) macrograpx x8 d) macrograpx x8

Fig. 4. The surface of a cylinder liner made of AW-6062 alloy coated with AHC (a) and of composite reinforced with Al_2O_3 fibres (b) before sliding and with transfer film (dark areas (2) on Figs c and d): b – fibres after matrix etching in the right bottom corner of figure; 1 – AHC, 2 – transfer film, 1a – AlMC

Rys. 4. Powierzchnia gładzi cylindrowej wykonanej ze stopu AW-6022 pokryta powłoką tlenkową (a) i tulei z kompozytu zbrojonego włóknami Al_2O_3 (b) przed współpracą i po współpracy c) i d): włókna Al_2O_3 odsłonięte w wyniku trawienia osnowy w prawym dolnym rogu; 1 – AHC, 2 – film ślizgowy, 1a – AlMC

During friction, a thin, almost continuous sliding film (in **Fig. 4c** on the left side of the border between the light AHC (1) and the dark (2) film is visible) of graphite and PTFE wear products is deposited on the AHC surface (**Figs. 4c and 5**). At the stage of wearing-in (up to 80h), the wear of TG15 is higher because the roughness valleys in the AHC are not yet filled with wear debris. In addition, the heat generated by friction reduces the strength of the material, making it easier to shear. Once the material contact has gone through the wearing-in phase, the thickness of the film, 2–4 µm (3 in **Fig. 5b**), is sufficient to separate the plastic material from the AHC. This film uses a surface layer that changes the initial plastic/ceramic contact into plastic/plastic contact. In this way, a hard material,

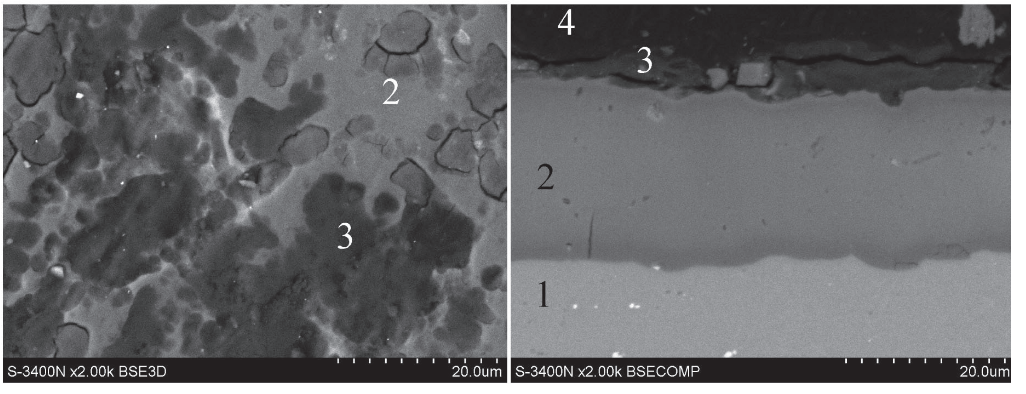


Fig. 5. Surface (a) and cross-section (b) of an oxide layer with plated by friction transfer film, SEM: 1 – matrix alloy, 2 – oxide layer, 3 – transfer film, 4 – resin for metallographic preparation

Rys. 5. Powierzchnia (a) i zgład (b) anodowej powłoki tlenkowej z naniesionym podczas tarcia filmem ślizgowym, SEM: 1 – stop osnowy, 2 – powłoka tlenkowa, 3 – film ślizgowy, 4 – żywica metalograficzna

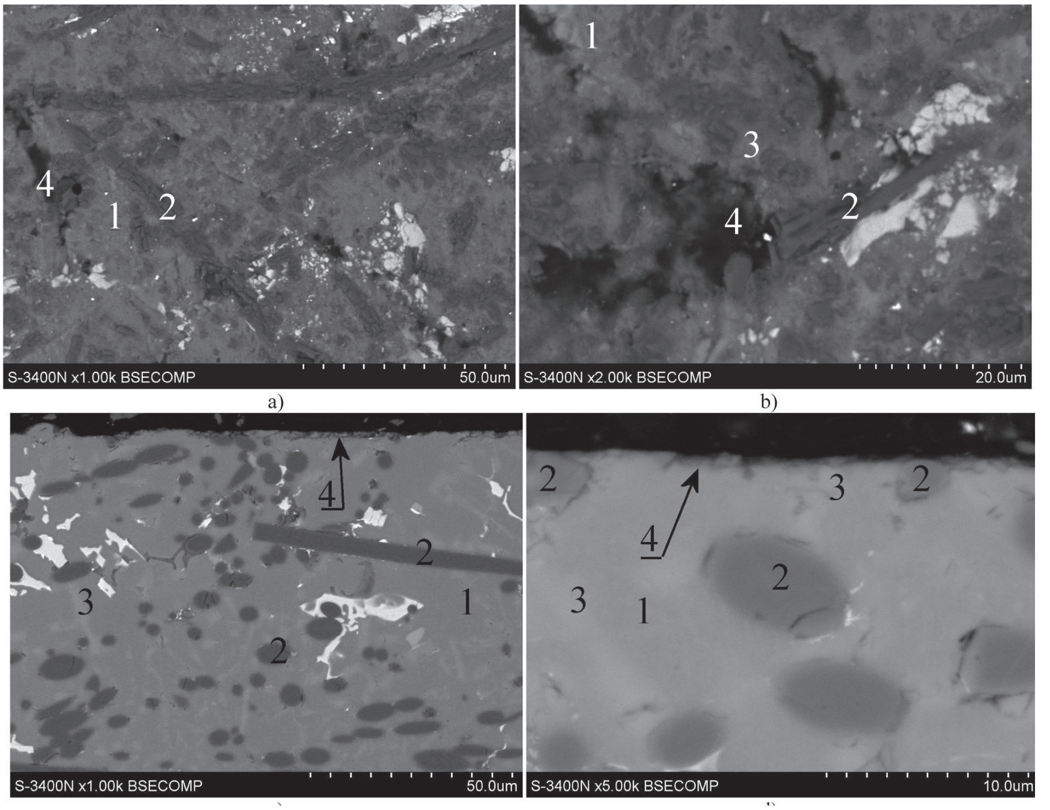


Fig. 6. Surface (a, b) and cross-section (c, d) of AlMC with transfer film: 1 – composite matrix, 2 – Al_2O_3 fibres, 3 – Si precipitates, 4 – transfer film

Rys. 6. Powierzchnia (a i b) oraz zgłady (c i d) AlMC z filmem ślizgowym: 1 – osnowa kompozytu, 2 – włókna Al_2O_3, 3 – wydzielenia Si, 4 – film ślizgowy i.e., polyacetal, and a very hard material, Al_2O_3, separated by a thin layer of sliding film with a low shear strength, work together, which is in line with the friction hypothesis of Ernst and Merchant. The film, by filling in the surface valleys of the AHC (**Fig, 5a**), reduces its roughness (Ra from 0.45 to 0.33 μm), which decreases the influence of the second component in the formula (1) and reduces the coefficient of friction.

The sliding film is also deposited on the composite's surface with Al_2O_3fibres (**Figs. 4d, 6**). The surface of 2–3 μm diameter fibres protruding (0.2 μm) above the matrix is not as developed as the AHC, and the polyamide matrix composite contains less soft, faster wearing components than TG15. Therefore, the film is thinner (of a lighter shade, **Fig. 4d**) and discontinuous, concentrated in the vicinity of Al_2O_3 fibres (4 in **Fig. 6**) and Si precipitates (**Figs. 6 and 7** – C and Si peaks). Another reason for the differences in the film's structure is the topography of the surface. The peaks of irregularities of the continuous AHC cut more intensively the material with a PTFE matrix with lower hardness (higher wear in the wearing-in phase, **Fig. 3a**). The less frequent (10% mass content) in AlMC fibres protruding over the matrix surface (0.2 μm, **Fig. 6d**), and the Si precipitates cut weaker the harder polyacetal matrix material (lower wear). The plastic sliding film on AlMC and the wear cause a decrease in surface roughness Ra from 0.1 to 0.08 μm.

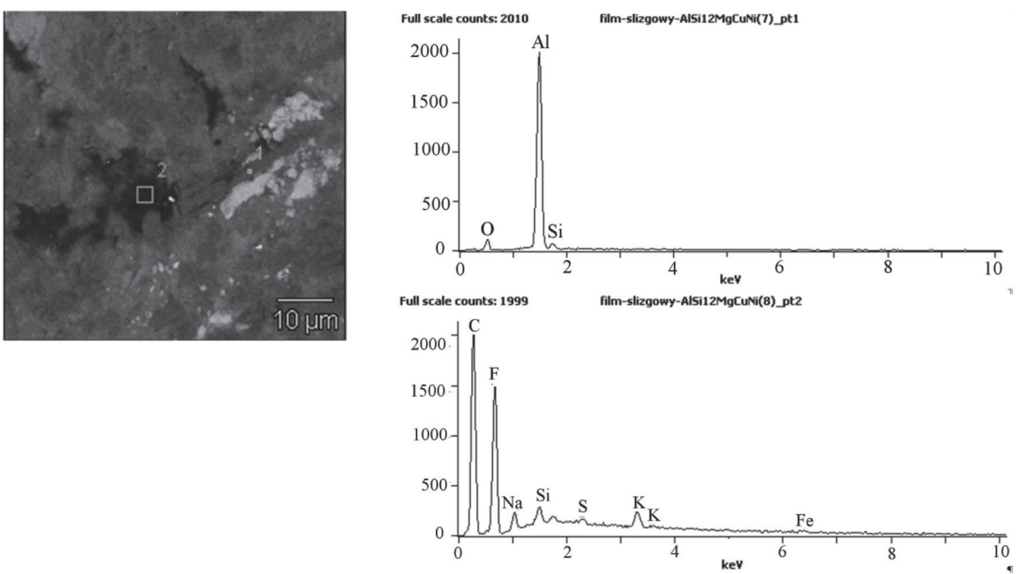


Fig. 7. Quality analysis at points 1 and 2 of AlMC surface after sliding (transfer film near Si precipitate)
Rys. 7. Analiza jakościowa w punktach 1 i 2 powierzchni AlMC po tarciu (film ślizgowy w pobliżu wydzieleń Si)

CONCLUSIONS

The following conclusions can be drawn based on the results of the tests:

1. The composite plastic material with a polyacetal matrix containing 15% of solid lubricants (PTFE, graphite, carbon fibres) slides against an aluminium alloy based composite (AC-47000+10% Al_2O_{3F}) under conditions of technically dry friction, forming on the surface of the composite a thin discontinuous sliding film which reduces the coefficient of friction and wear compared to the previously used contact: PTFE+15% $C_{gr)}$/Anodic Hard Coating.
2. The use, in the designing of a technical means of transport, of an oil-free contact: a composite plastic material containing solid lubricants (PASL) sliding against an aluminium alloy based composite containing Al_2O_3 fibres and Si precipitates, will allow reducing environmental pollution at the production stage (elimination of electrochemical treatment and after production wastes) and operation (less dusting caused by reduced wear).

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