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TRIBOLOGICAL WEAR ANALYSIS OF Ti-Al COMPOSITE COATINGS APPLIED WITH THE COLD SPRAY METHOD

ANALIZA ZUŻYCIA TRIBOLOGICZNEGO KOMPOZYTOWYCH POWŁOK Ti-Al NANOSZONYCH METODĄ COLD SPRAY

Key words: composite coatings, Ti-Al, LPCS, tribological testing.

Abstract: The possibility of using the low-pressure cold gas spraying (LPCS) method to create composite coatings has been known and used for a long time. This method makes it possible to create coatings from physically and chemically different powders and to regenerate components damaged during operation. Composite coatings of titanium and aluminium at different weight concentrations were selected for the study. The research was conducted to optimise the influence of the chemical composition of the composite coatings on their tribological properties. This paper presents the results of tribological wear testing of composite coatings applied using the low-pressure cold gas spray (LPCS) method. Wear resistance tests were performed using the ball-on-plate method in reciprocating motion using a steel ball. Tribological testing of the coatings included determining the effect of contact force on wear and the value of the kinetic coefficient of friction of the friction pairs tested. The study determined the optimum chemical composition of the Ti-Al composite coatings to improve wear properties.

Słowa kluczowe: powłoki kompozytowe, Ti-Al, LPCS, badania tribologiczne.

Streszczenie: Możliwość zastosowania metody niskociśnieniowego natrysku zimnym gazem (LPCS) do tworzenia powłok kompozytowych jest znana i wykorzystywana od bardzo dawna. Metoda ta pozwala na tworzenie powłok z różnych pod względem fizycznym i chemicznym proszków oraz na regenerację elementów uszkodzonych podczas eksploatacji. Do badań wybrano kompozytowe powłoki tytanu i aluminium przy różnych stężeniach wagowych. Badania przeprowadzono w celu optymalizacji wpływu składu chemicznego powłok kompozytowych na ich właściwości tribologiczne. W pracy zaprezentowano wyniki badań zużycia tribologicznego powłok kompozytowych nanoszonych z zastosowaniem metody niskociśnieniowego natrysku zimnym gazem (LPCS). Badania odporności na zużycie wykonano przy użyciu metody ball-on-plate, w ruchu posuwisto-zwrotnym z wykorzystaniem stalowej kulki. Badania tribologiczne powłok obejmowały określenie wpływu siły nacisku na zużycie oraz wartość współczynnika tarcia kinetycznego badanych par trących. Badania pozwoliły określić optymalny skład chemiczny kompozytowych powłok Ti-Al w celu poprawy właściwości eksploatacyjnych.

INTRODUCTION

Due to the worldwide economic crisis, new and cheaper solutions are needed, relying on the possibility of locally improving or remanufacturing already functioning components. Among others, in such strategic industries as aerospace and biomedical engineering. We have a great deal of technical expertise that enables us to do a wide range of things that can significantly reduce the cost of manufacturing new components.

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Several methods and technologies are available for remanufacturing in areas of localised material degradation. In the low-pressure cold gas spray (LPCS) method, damaged surfaces that were previously corroded and those that have been exposed to mechanical damage during operation can be regenerated **[L. 1–3]**. In addition, with the knowledge of the exposure of this area to particularly demanding operating conditions, we can modify it in any way we wish by optimising the chemical composition of the coatings, thereby changing the mechanical or tribological properties of the final component **[L. 3–5]**. The repair consists of applying a sufficiently thick coating to the damaged surface of the component, which must first be properly cleaned of oxides and impurities. Then, through selected surface treatment, the original geometry of the reusable component is restored. As part of the remanufacturing of damaged parts, it is also possible to modify the surface by means of surface finishing to increase their performance. LPCS technology makes it possible to create durable, highly adhesive and multi-phase coatings without interfering with the component's substrate **[L. 1, 3, 6]**.

Titanium components are very expensive to manufacture due to the costly process of obtaining titanium and its difficult-to-machine properties **[L. 7–9]**. Therefore, repairing titanium components is a great and environmentally friendly solution. In the aerospace industry, which is based on light metal alloys **[**L. insert**]**, when remanufacturing titanium components, aluminium components or their alloys, it is possible to dope the base powder of titanium with aluminium powder **[L. 10–14]**. Among other things, the modification can reduce the oxidation of the coatings, which translates into an increase in the mechanical properties of the coatings and the finished component. The addition of a ductile material, such as aluminium, enables the formation of a metallic matrix for hard and difficult-to-deform titanium. In addition, the Ti-Al composite coatings show a higher resistance to corrosion phenomena. Research has shown that the application of titanium and aluminium increases the strength parameters of components used in the aerospace industry **[L. 9]**.

The study aimed to use LPCS spraying to regenerate worn or damaged machine components. Coating technology was chosen to allow the raw titanium powder to be doped with aluminium powder. In addition, the effect of the modification on the microstructure, hardness and tribological parameters of the Ti-Al composite coatings was characterised. The research was exploratory in nature, and based on this research, the amount of modifying phase was selected while maintaining a consistent and durable Ti-Al. Composite coating allowed optimum tribological parameters to be obtained.

MATERIALS AND MEASURING METHODS

Ti-Al composite coatings were used for the study. Due to the high hardness and lack of titanium deformability, obtaining coatings from technically pure titanium was impossible. Due to their ease of application, aluminium coatings were used as a reference material. A commercially available aluminium powder with a morphology of elongated rounded particles and a fraction size of 20-80 µm was used for the study. A commercial titanium powder with a morphology of differently shaped and sharply pointed particles ranging from 20–80 µm was also used for the modification. The mass proportion of titanium was selected based on the preliminary studies on the coatings' microstructure. The powders were mixed using a laboratory grinder for 60 min.

Tribological tests were carried out on aluminium (Al) coatings and coatings modified with 60% and 70% by crystalline titanium powder (Ti) weight.

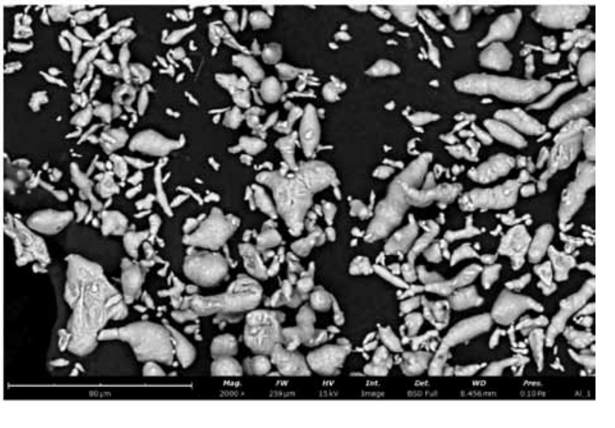

Fig. 1. Morphology of aluminium powder. SEM
Rys. 1. Morfologia proszku aluminium. SEM

Aluminium and Ti-Al composite powders were applied using low-pressure cold gas spraying (LPCS). Optimum process parameters (**Table 1**) were determined experimentally to apply the coatings.

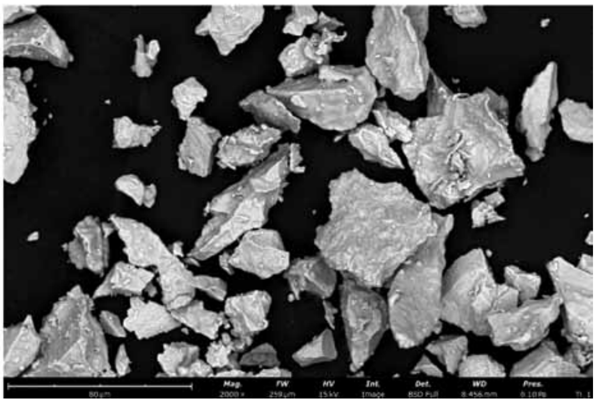

Fig. 2. Morphology of titanium powder. SEM
Rys. 2. Morfologia proszku tytanu. SEM

Table 1. Coating parameters, LPCS method
Tabel 1. Parametry nanoszenia powłok, metodą LPCS

Powder	Gas preheating temperature	Gas pressure	Traverse speed
Al, Ti-Al	400°C	0.9 MPa	10 mm/s

Tests of the friction process were conducted on a test stand constructed at the Department of Fundamentals of Mechanical Engineering and Tribology of Wrocław University of Science and Technology (**Figure 3**). The equipment enables tests of sliding friction in alternating motion **[L. 15]**. During the tests, a steel ball was pressed against a steel plate with the coating under test with force F_n via weights.

The system moving the plate consisted of two carriages lying on top of each other, bearing so that they could move in the same direction. The assembly was driven by an electric actuator comprising a stepper motor and a helical gearbox. During extension, the actuator moved the larger carriage, on which the smaller carriage was placed. The movement force was transmitted from the larger carriage to the smaller carriage via a strain gauge force sensor. The range of movement of the smaller carriage relative to the larger carriage is equal to the value of the force sensor deflection and clamping elements under the frictional force F_t.

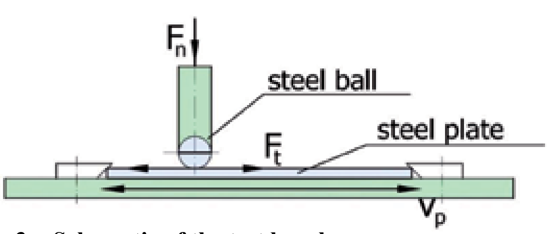

Fig. 3. Schematic of the test bench
Rys. 3. Schemat stanowiska pomiarowego

A coated sample mounted on a moving carriage performed a series of 200 movement cycles during each of the three measurement series. A movement cycle consisted of two movements (v_{smax} = 5 mm/s) in both directions. The movement time in each direction was 0.4 s. The load on the friction node was 20 N.

Steel bearing balls d = 4 mm (3.969 mm) were used for the tests. The tests were conducted under technically dry friction conditions. Prior to the measurements, the surfaces of the coatings were ground, polished and cleaned to homogenise the surfaces.

In order to study the morphology of the metal powders and the microstructure of the coatings, studies using a Phenom XL scanning electron microscope were used. A Leica DCM8 profilometer was used for surface analysis**.**

For the tested coatings, microhardness measurements were carried out using the Vickers method with a load of 1,000 g (9.81 N), with five measurements each, and with a load of 500 g (4.9 N), similarly. The measurement was carried out in accordance with EN ISO 6507-1.

RESULTS AND DISCUSSION

Microstructure

Based on the microscopic examination, it was found that the tested coatings showed a compact and homogeneous microstructure in terms of morphology. All the tested coatings achieved high adhesion to the substrate and high coating quality.

Microstructure analysis of the aluminium Al coatings showed a low degree of porosity. The lower density of the Al coatings can be seen in areas of incomplete matching, the developed surface of the aluminium powder particles (**Fig. 4**). In the Ti-Al composite coatings, potential areas of porosity were filled with deformed aluminium powder particles, forming a matrix of hard and undeformed titanium particles (**Figs. 5-6**).

Hardness

The average microhardness values measured on the cross-sections and the determined standard deviations for the tested materials are shown in **Table 2**. For the coating made of aluminium only, the average hardness values are 39HV0.5 and 35HV1, respectively. In the individual tests, slight differences in hardness values were observed, depending on the porosity of the measurement site.

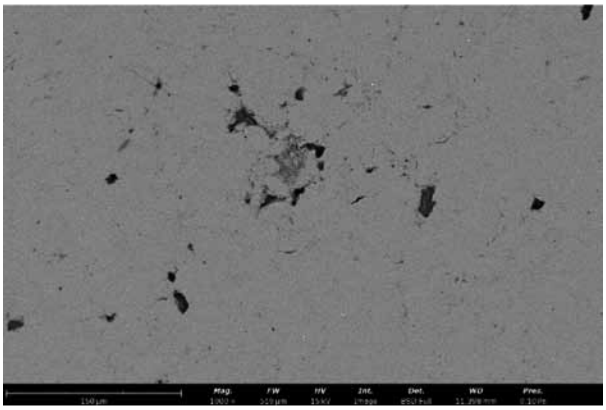

Fig. 4. Micromorphology of layer Al100 SEM
Rys. 4. Mikromorfologia warstwy Al100 SEM

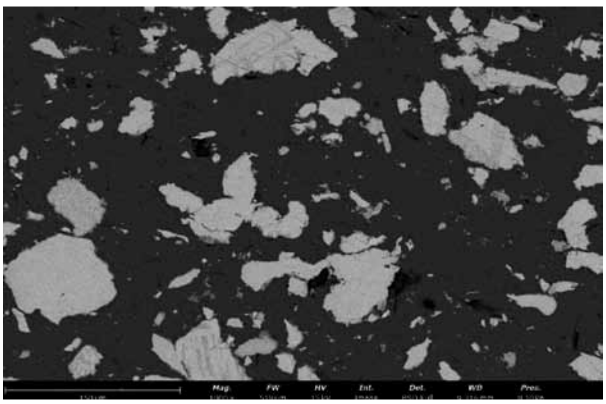

Fig. 5. Morphology of layer Ti60Al40 SEM
Rys. 5. Morfologia warstwy Ti60Al40 SEM

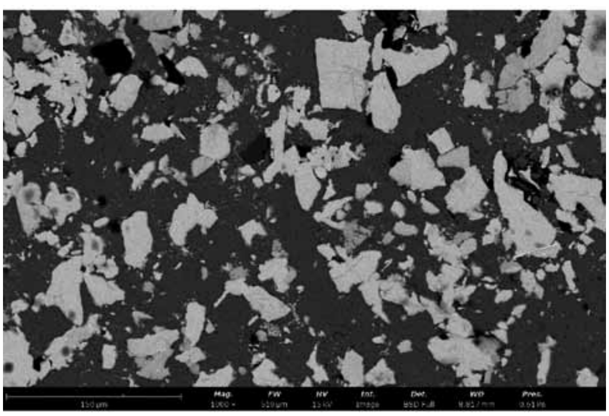

Fig. 6. Morphology of layer Ti70Al30 SEM Hardness
Rys. 6. Morfologia warstwy Ti70Al30 SEM

For the Ti60-Al40 coating, the highest microhardness values are 51HV0.5 and 49HV1. The lowest values are 39HV0.5 and 42HV1. The discrepancy between the microhardness results for this coating may be due to where the measurement was taken. If the area where the hardness was measured consisted mainly of Al grains, the result obtained was significantly lower than the microhardness in the coating section containing more Ti particles. The average hardness value for the Ti60-Al40 coating made using the LPCS method is 43HV0.5 and 45HV1.

For the Ti70-Al30 coating, the highest hardness values are 61HV0.5 and 59HV1, and the lowest are 57HV0.5 and 56HV1, respectively. The difference between the extreme results of the measurements obtained for this coating is 11HV0.5 and 8HV1. The value of the measurement results obtained, as in the Ti60-Al40 coating, depends on the area in which the measurement was taken. In contrast, the average value of the microhardness measurements for the Ti70-Al30 coating is 56HV0.5 and 57HV1.

Table 2. Averaged hardness measurements
Tabela 2. Uśrednione pomiary twardości

Coating	HV0.5	σ	HV1	σ
Al	39	3.8	36	2.1
Ti60-Al40	43	6.2	45	2.1
Ti70-Al30	56	4.0	57	2.9

Coefficient of friction

Analysis of the kinetic friction coefficient values, under a load of 20 N, for the coatings tested showed that the addition of a modifying phase, in the form of 60 and 70% titanium powder, causes a reduction in the coefficient value. A reduction in the friction coefficient was observed from 0.68 for pure aluminium to 0.5 for 60%Ti and 0.48 for 70%Ti (**Fig. 7**). By comparing the determined values of friction coefficient and microhardness, it can be

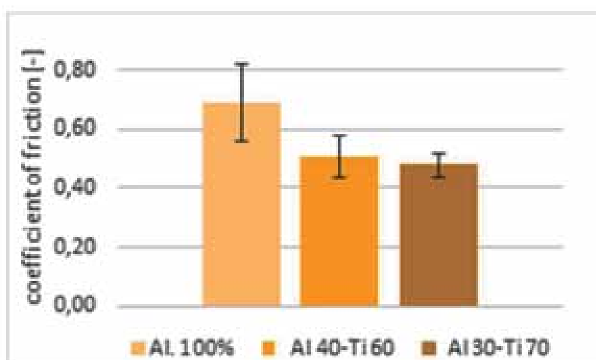

Fig. 7. Summary of averaged friction coefficient values, for aluminium coatings and Ti-Al composite coatings, under 20 N loading
Rys. 7. Zestawienie uśrednionych wartości współczynnika tarcia dla powłok aluminiowych oraz kompozytowych powłok Ti-Al przy obciążeniu 20 N

assumed that a reduction in the contact area of the friction node causes the decrease in resistance to motion. The harder the structure, the smaller the cavity of the ball in the material, which translates into a decrease in the surface area of adhesive interactions and a decrease in the volume of the coating material, which is deformed and micro-cracked during friction.

Profilometric testing

An analysis of the surface topography of the coatings after friction tests was carried out. The tests showed that, due to the contact between the coatings and the ball, there is uniform wear of the coatings. The nature of wear was determined to be abrasive with a dominant plastic deformation mechanism. In no case was brittle spalling of coatings observed. The aluminium and Ti-Al composite coatings show a high degree of plasticisation, and the modifying phase does not change this character. This is also confirmed by the values of the friction coefficient results recorded for all types of coatings tested.

Based on the analysis of the grooves formed on the surface of the coatings as a result of friction, grooves were observed on both sides of the abrasion. These testify to the plastic deformation of the coatings due to frictional interaction with the steel ball. This phenomenon is typical of soft aluminium (**Figure 8**). Similar mechanisms were observed for Ti-Al composite coatings. (**Figs. 9–10**), in which a higher proportion of the reinforcement is the hard titanium phase. Due to the width of the groove recorded for aluminium exceeding the imaging range for the profilometer, only a fragment of the wipe/rust surface is visible for aluminium.

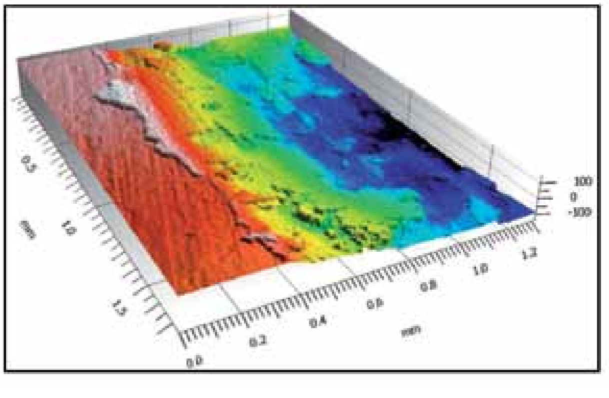

Fig. 8. Example of a groove formed after tribological tests carried out on an Al coating with a load of 20 N

Rys. 8. Przykładowa bruzda powstała po badaniach tribologicznych przeprowadzonych na powłoce Al przy obciążeniu 20 N

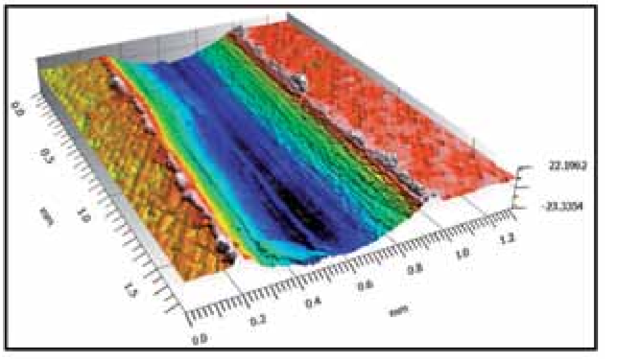

Fig. 9. Example of a groove formed after tribological tests carried out on a 60Ti-Al coating under a 20 N load

Rys. 9. Przykładowa bruzda powstała po badaniach tribologicznych przeprowadzonych na powłoce 60Ti-Al przy obciążeniu 20 N

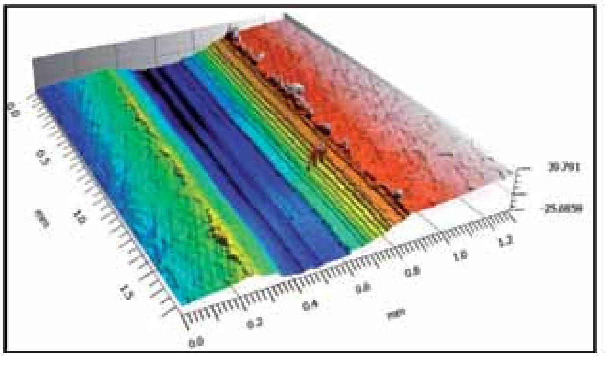

Fig. 10. An example of a groove formed after tribological tests conducted on a 70Ti-30Al composite coating under a 20 N load

Rys. 10. Przykładowa bruzda powstała po badaniach tribologicznych przeprowadzonych na kompozytowej powłoce 70Ti-30Al przy obciążeniu 20 N

Analysis of the depth of the grooves created after tribological testing showed that, for the aluminium coatings, the penetration of the ball into the coating averaged 230 μm (**Fig. 11**). With an increase in the percentage of titanium, a reduction in the depth of abrasion was found at a similar level by an average of 30 μm (**Figs. 12** and **13**). The introduction of the modifying phase does not result in a change in the depth of the obtained groove,

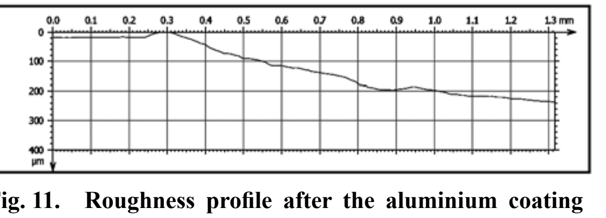

Fig. 11. Roughness profile after the aluminium coating friction process

Rys. 11. Profil chropowatości po procesie tarcia powłoki aluminiowej while slight changes in the width of the groove were observed. For the Ti70-30Al coating, a reduction in the width of the groove by an average of 10 µm, compared to the Ti60-40Al coating, was recorded, which can be seen in the roughness profiles of the abrasion surface.

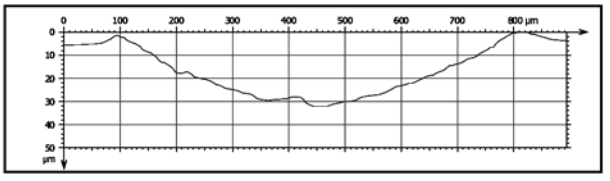

Fig. 12. Roughness profile after the friction process of the 60Ti-40Al coating

Rys. 12. Profil chropowatości po procesie tarcia powłoki 60Ti-40Al

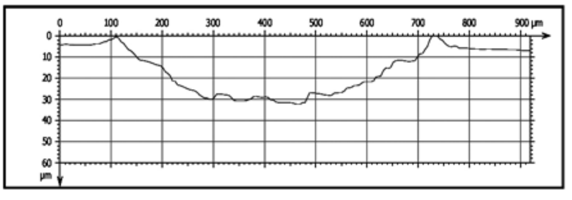

Fig. 13. Roughness profile after the friction process of the 70Ti-30Al coating

Rys. 13. Profil chropowatości po procesie tarcia powłoki 70Ti-30Al

Microscopic observations

Observations of the abrasion surface after tribological testing using scanning electron microscopy methods showed that the aluminium coating exhibits a clearly plastic character (**Fig. 14**). The changes have the character of plastically deformed coating fragments. A clear area of efflorescence formed due to friction with the steel ball can be seen. The presence of aluminium coating material was also observed on the ball surface, indicating high adhesion between the coating material and the ball. This makes it possible to conclude that adhesive wear also occurs in the tested material associations. (**Figure 15**).

Testing of Ti-Al composite coatings showed plastic deformation of the coating in the friction area (**Figs. 16-17**). Small transverse delaminations (crevices) visible on the friction surface testify to high adhesion and significant tensile forces in the coating material. The frictional forces caused by adhesion damage the material below the abrasive wear area.

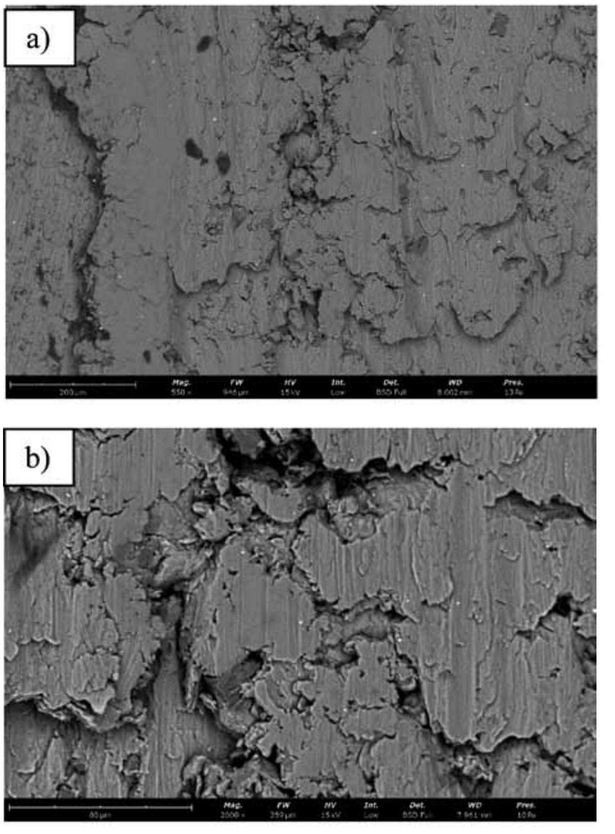

Fig. 14. a) Example of a groove formed after tribological tests conducted on an aluminium coating, b) enlarged section of image a). SEM

Rys. 14. a) Przykładowa bruzda powstała po badaniach tribologicznych przeprowadzonych na powłoce aluminiowej, b) powiększony fragment obrazu a). SEM

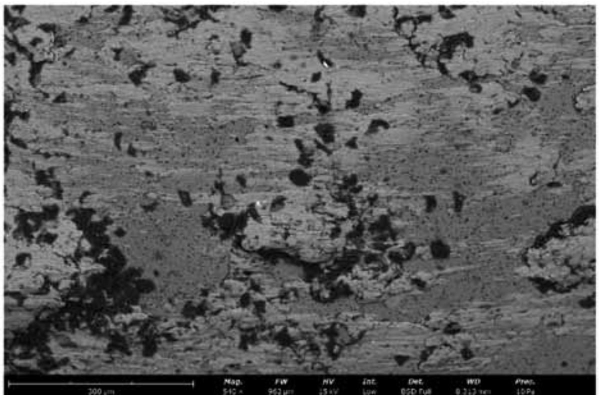

Fig. 15. Surface of a steel ball after tribological testing with spread coating products. SEM

Rys. 15. Powierzchnia kulki stalowej po badaniach tribologicznych, z rozsmarowanymi produktami powłoki. SEM

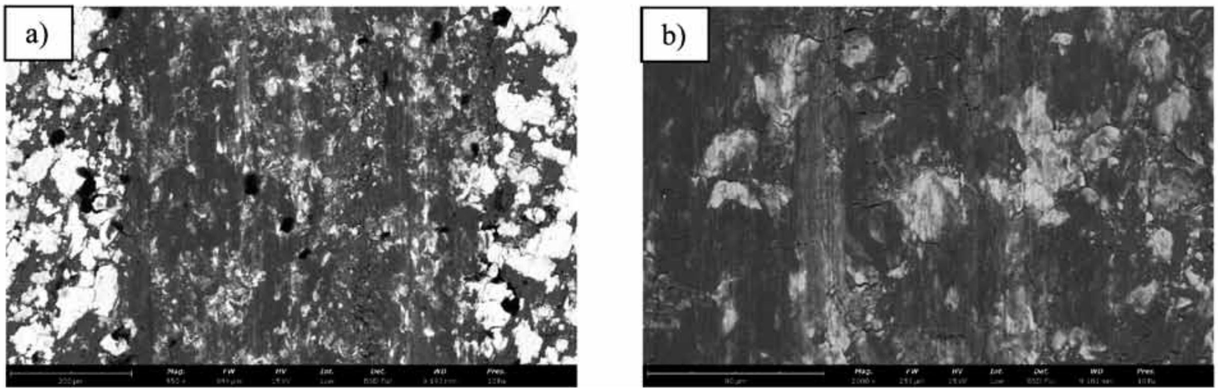

Fig. 16. a) Example of a groove formed after tribological tests carried out on the coating, b) enlarged section of image a). SEM

Rys. 16. a) Przykładowa bruzda powstała po badaniach tribologicznych przeprowadzonych na powłoce, b) powiększony fragment obrazu a). SEM

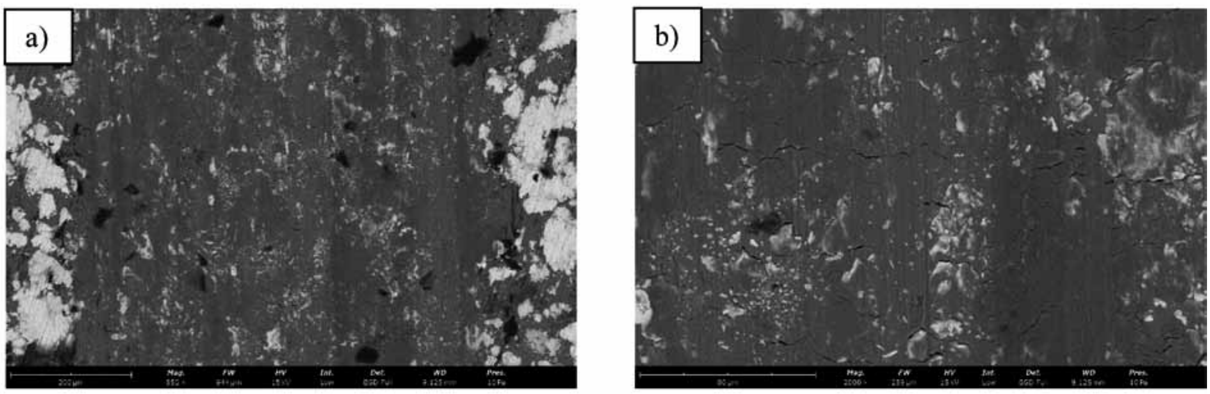

Fig. 17. a) Example of a groove formed after tribological tests conducted on a Ti70-Al30 composite coating, b) enlarged section of the image (a). SEM

Rys. 17. a) Przykładowa bruzda powstała po badaniach tribologicznych przeprowadzonych na kompozytowej powłoce Ti70-Al30, b) powiększony fragment obrazu a). SEM

CONCLUSIONS

The research leads us to make the following conclusions:

- The use of the low-pressure cold gas spraying method makes it possible to produce durable Ti-Al composite coatings with a high proportion of the titanium phase. Coating morphologies of sufficiently high quality were found for both 60 and 70 wt.% of the titanium phase. The composite coatings show low porosity and high adhesion to the substrate.

Measurements of hardness showed an almost twofold increase in this parameter in the composite coating with the highest proportion of the titanium phase – 70% 57HV1, compared to the aluminium coating 36HV1. At a titanium share of 60%, an increase in hardness was found from 36HV1 to 45HV1.

- Based on tribological tests, it was found that aluminium coatings produced using the LPCS method show a high degree of plasticity, which translates into a significant deformation of the material during friction and a high value of the friction coefficient $\mu = 0.68$. The production of 60 and 70 wt.% titanium composite coatings with the remaining share of the aluminium phase decreases the friction coefficient. This is related to an increase in hardness and, thus, a decrease in groove depth and friction surface area in the contact zone, resulting in a decrease in the friction coefficient value from 0.68 for pure aluminium to 0.5 for 60%Ti and 0.48 for 70%Ti.

- The nature of the analysis of the changes on the surface of the coatings after the friction process showed a reduction in the depth of the abrasion profiles with increasing titanium content. Observation of images recorded using scanning electron microscopy methods showed the absence of brittle changes in the coatings.
- The optimum amount of modifying phase, in Ti-Al composite coatings, in the amount of 70% titanium and 30% aluminium, was identified based on the research carried out. By using the optimum parameters of the low-pressure cold gas spray application technology and such a chemical composition, it is possible to obtain the correct coating morphology and correspondingly high tribological parameters.

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