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COMPARATIVE STUDIES OF TRIBOLOGICAL PROPERTIES OF SELECTED POLYMER RESINS FOR USE IN HYDRAULIC SYSTEMS

BADANIA PORÓWNAWCZE WŁAŚCIWOŚCI TRIBOLOGICZNYCH WYBRANYCH ŻYWIC POLIMEROWYCH DO ZASTOSOWAŃ W UKŁADACH HYDRAULICZNYCH

Key words:	composites, hydraulic cylinder, epoxy, polyurethane.
Abstract	The use of composite materials in the construction of hydraulic cylinders allows for a significant reduction in the weight of the element while maintaining its operating parameters. One of the issues to be solved at the design stage is to ensure the tightness of the cylinder and the correct cooperation of the cylinder with the piston. Four materials that can be used as internal coatings in such composite cylinders were selected in the work. Preliminary tests using the ball-on-disk method and observation of signs of wear were carried out using an optical microscope and SEM. After testing, materials for further studies were selected.
Słowa kluczowe:	kompozyty, siłownik hydrauliczny, żywica epoksydowa, poliuretan.
Streszczenie	Wykorzystanie materiałów kompozytowych w konstrukcji siłowników hydraulicznych pozwala na znaczne zmniejszenie masy elementu, przy jednoczesnym zachowaniu jego parametrów pracy. Jednym z zagadnień, które trzeba rozwiązać na etapie projektowym, jest zapewnienie szczelności cylindra oraz prawidłowej współpracy cylindra z tłokiem. W pracy wytypowano cztery materiały mogące znaleźć zastosowanie jako powłoki wewnętrzne w takich kompozytowych cylindrach. Przeprowadzono badania wstępne metodą ball on disk oraz obserwacje śladów zużycia przy wykorzystaniu mikroskopu optycznego oraz SEM. Po przeprowadzeniu prób wytypowano materiały, które wykorzystane zostaną w dalszych badaniach.

INTRODUCTION

To increase the durability, reliability, and energy efficiency of devices, as well as reduce the costs of their production, it is necessary to search for better and more modern materials. In recent decades, there has been a growing interest in replacing metal alloys with plastics and composite materials. Attempts are also being made to use these materials in friction pairs on an increasing scale [L. 1]. The reasons for this approach to the construction of machine elements are, among others, the lower weight of plastics, the ease of processing, and low costs.

Similar development trends can be seen in the design of components for use in hydraulic systems and drives [L. 2]. One of the key advantages of a hydraulic drive (in addition to the favourable ratio of transferred energy to mass and ease of control and adjustment) is the ability to freely arrange the elements of the system and separate the generator and control elements from the actuators. This is especially desirable when the designer wants to achieve a favourable weight distribution of the machine. Conventional actuators (motors and cylinders) are usually massive steel devices and placed, e.g., on arms or booms, can cause significant static and dynamic loads on the structure. The materials from which they

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are made are subject to corrosion and are not electric or magnetic inert. The literature presents attempts to make hydraulic cylinders from composite materials [L. 3]. In many such elements, however, an internal, thin-walled steel pipe (so-called liner) was used to ensure tightness and proper tribological conditions at the cylinder-piston interface [L. 4]. While the mass reduction of the element obtained in this way is significant, this does not solve the issue of corrosion or susceptibility to magnetic fields. It also introduces additional problems resulting from the combination of two different materials, significantly different from each other in mechanical or thermal properties. This generates problems associated with different thermal expansion coefficients resulting in internal stresses. Therefore, it seems reasonable to develop a composite hydraulic cylinder structure without an internal steel liner, where proper tribological conditions of the cylinder-piston interface would be ensured by a specially selected polymer or nanocomposite layer [L. 5].

New materials that can be used in hydraulic drive components are as follows [L. 4, 5]:

1. Epoxy resins – substances containing epoxy groups, formed as a result of polyaddition of bisphenol and epichlorohydrin. Curing of an epoxy resins is an irreversible process and is carried out by using, e.g., amine hardeners. Depending on the formulation, this process is carried out at ambient temperature or at an elevated temperature according to the recommended curing cycle. Due to their favourable price, ease of processing, low weight, and good mechanical properties, these materials are widely used as composite matrixes, structural adhesives, and protective coatings.
2. Polyurethanes – materials formed most often as a result of the reaction of isocyanates with polyols. They can be in the form of elastomers, foams, as well as rigid materials. Unlike epoxy resins, solid polyurethanes are thermoplastics and can be processed many times. They are used in the furniture, automotive, footwear, and construction industries, as well as for the production of gaskets, adhesives, or hobby casting.
3. Composites – materials consisting of at least two phases – matrix and filler – which allows obtaining properties that are better than those of the base materials. In the case of tribological composites, the reinforcement is usually a powder or lamellar form and includes metal powders (e.g., copper, iron, nickel) and their oxides (e.g., aluminium oxide, copper oxide, iron oxide, titanium oxide), non-metallic oxides (silicon, zirconium) and other materials such as silicon carbide, boron carbide, boron nitride, titanium nitride, or plastics. Scientists are also interested in the addition of soot as a way to use waste from coal-fired power plants. Thanks to such fillers, it is possible to reduce the coefficient of friction and reduce the wear of matrix material without losing its other properties

(low weight, ease of processing). It has been noticed that reducing the diameter of the filler directly leads to an improvement in the mechanical properties of materials such as tensile strength and Young's modulus [L. 6], so tests with fillers of ever finer granulation are conducted. Powders whose particle diameter is less than 100 nm are called *nanopowders*, and composites made using such nanofillers are called *nanocomposites*. It has been shown that the use of nanofillers improves mechanical properties such as Young's modulus and tensile strength [L. 7] but also impact resistance [L. 8], the friction coefficient [L. 8], and wear [L. 8–10]. Adhesion [L. 11] and anti-corrosion [L. 12, 13] also improved in studies.

As can be seen in the examples cited, intensive work is conducted in hydraulic systems to replace steel elements with elements made of lighter materials that are easier to manufacture. Therefore, the purpose of this paper is to determine the tribological properties of materials selected for internal coatings in the cylinder of a composite hydraulic cylinder. The friction in the cooperating piston-cylinder pair and the wear of these elements significantly limit the use of available materials. This forces the initial analysis of materials in terms of wear resistance and potential system efficiency, determined, e.g., by measuring the coefficient of friction.

MATERIALS

Materials selected for availability, easy processing, good adhesion to composite materials, as well as promising mechanical and tribological properties, were tested. The choice of materials for research was also influenced by the literature analysis and whether earlier attempts were made to use these materials in hydraulic systems [L. 2]. Ultimately, coatings from selected materials will be applied to steel mandrels by spraying to obtain coatings 1-2 mm thick. After crosslinking, the cylinders will be made of epoxy resin reinforced with carbon fibre by filament winding method. Such a cylinder will operate in a hydraulic system at pressures up to 20 MPa and temperatures up to 80 degrees Celsius.

The first material was a two-component polyurethane F180 resin from Sika characterized by low viscosity (60 mPa*s at 25°C) and short curing time (3.5 min).

Another material was the Huntsman Araldite LY 1564 epoxy resin with Aradur 3487 hardener, designed to make composites by infusion and winding methods (Epoxy). It was also characterized by low viscosity (200–300 mPa*s at 25°C), good mechanical properties, and a gel time around 2–3 hours in ambient conditions.

The third material was a commercially available Belzona 1111 Super Metal. It is a mixture of epoxy and novolac resins with various types of fillers, e.g., compounds of aluminium, calcium, silicon, iron, or

magnesium. The manufacturer recommends this material for protective applications on metal parts and for filling defects in elements subject to regeneration. The product has good machinability and a very high viscosity (paste consistency), which prevents casting.

The basic mechanical and thermal properties of the Epoxy, F180, and 1111 materials tested are summarized in **Table 1**.

The last material tested was epoxy resin with the addition of 2% by weight nanosilica (Epoxy + 2%SiO₂). As a filler, a commercially available product called Nanopox A410 from Evonik was used. It is a mixture of epoxy resin and silica with a maximum particle diameter of 50 nm and a filler content of 40% by weight. The test material was created by manually mixing the base resin (Araldite LY 1564), an additive containing a filler and a hardener (Aradur 3487) for 5 min in proportions allowing obtaining a material with a content of 2% nanofiller by weight.

Table 1. Basic mechanical and thermal properties of tested materials

Tabela 1. Podstawowe właściwości mechaniczne i termiczne badanych materiałów

Name	F180 polyurethane	Araldite 1564/3487 epoxy	Belzona 1111
Density [g*cm ⁻²]	1.06	1.11	2.5
Shore D hardness	74	–	84
Flexural modulus [MPa]	1130	3200	7200
Flexural strength [MPa]	34	130	63
Pot life [min]	3.5	130-170	15
Glass transition temperature [°C]	98	83	–

Samples from F180, Epoxy and Epoxy + 2%SiO₂ materials were cast in silicone moulds. To make samples from 1111 material, first Epoxy substrates were made, and then a layer of 1111 material was applied to them. According to the manufacturer's recommendations, the F180 material was cross-linked only in the open air, while Epoxy, Epoxy + 2%SiO₂ and 1111 were additionally hot-cured (Epoxy and Epoxy + 2%SiO₂ for 8h at 80°C, 1111 for 4h at 80°C). All samples were subjected to grinding and polishing before testing.

METHODS

Tribological tests were performed using the ball on disk method using the T-11 tribotester manufactured by the Institute of Sustainable Technologies in Radom. Measurements were made at 21°C. The samples used were disks with a diameter of 1" and a height of 6 mm made of test materials. Counter-samples were balls made of 100Cr6 bearing steel, with a dimension of ¼" made in the 10th grade of accuracy and dimension group S = 0 µm. The hardness of the balls was 60–62 HRC. During the tests, the value of friction force and the change in the position of the ball in the vertical axis were recorded. This method was chosen because of its simplicity and ease of making samples. The aim of the research was the initial selection and comparison of materials for anti-wear coatings. Therefore, it was only limited to studies in the ambient conditions, as well as using the ball-on-disk method, which is widely recognized as an easy and reliable method for such preliminary studies.

When determining the range of input quantities (by the repetition method), the requirement was set that the test subject must function properly in all systems of input values and not seizure. Efforts were made to mirror the actual operating conditions occurring in hydraulic cylinders [L. 14]. The test parameters chosen according to literature [L. 15] were as follows:

- Load – 9.81 N,
- Linear speed – 0.3 m/s (which corresponded to 781 rpm),
- Friction path – 2160 m (corresponding to a test time of 2 hours),
- Ambient conditions were controlled and unchanged during all tests.

The output was the friction force and wear, measured by the depth and width of the friction path of the samples using a Phenom Pro-X scanning electron microscope. An additional parameter controlled during the test was weight loss, which due to the hygroscopicity of some materials was not taken into account.

Tests were repeated four times for each measurement point. The results were statistically processed at a 95% confidence level using Student's t-test. Error bars on the graphs show standard deviation values.

RESULTS

Four samples of each material were tested. **Figures 1–4** show examples of friction force and ball displacement charts for the tested materials as a function of time.

Figure 5 shows the maximum friction force of the steel ball on the sample. The lowest force was recorded for Epoxy and F180 materials, while a much higher force was observed in the case of 1111. Samples from Epoxy + 2%SiO₂ were discarded because they seized.

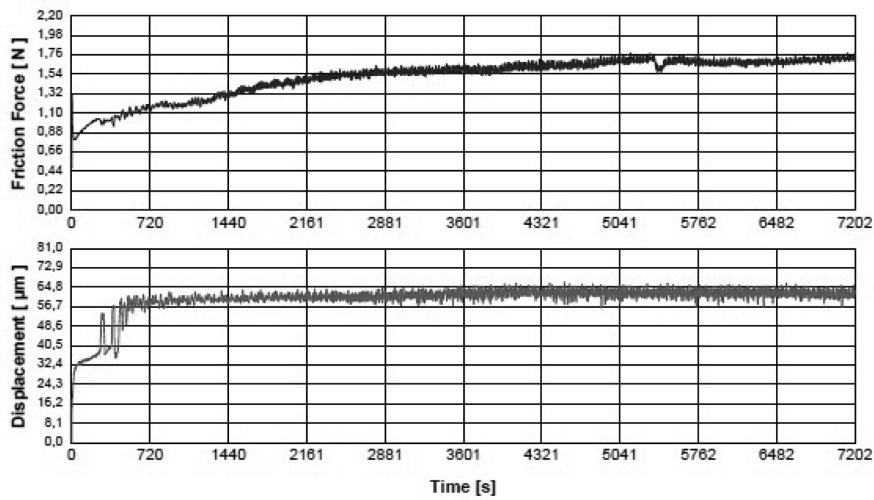


Fig. 1. Examples of friction force and ball displacement charts for F180 material
 Rys. 1. Przykładowe wykresy siły tarcia i zagłębienia kulki w czasie dla materiału F180

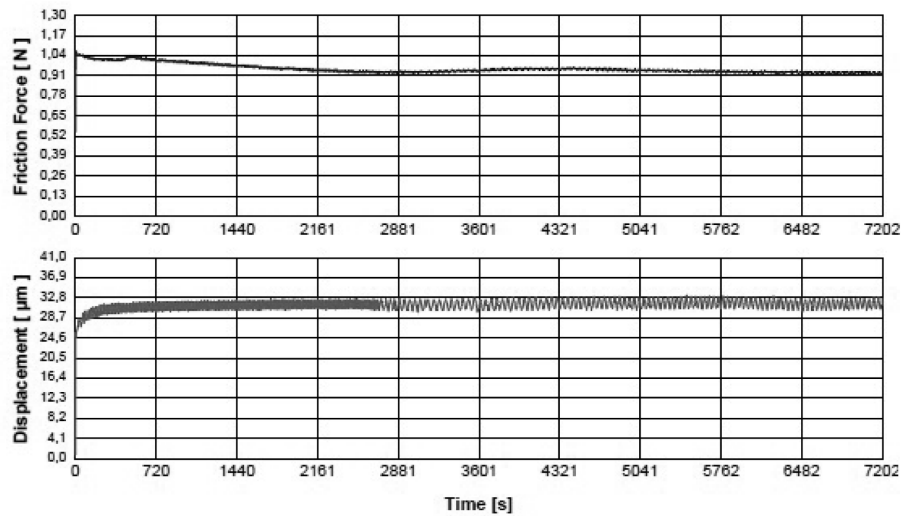


Fig. 2. Examples of friction force and ball displacement charts for Epoxy material
 Rys. 2. Przykładowe wykresy siły tarcia i zagłębienia kulki w czasie dla materiału Epoxy

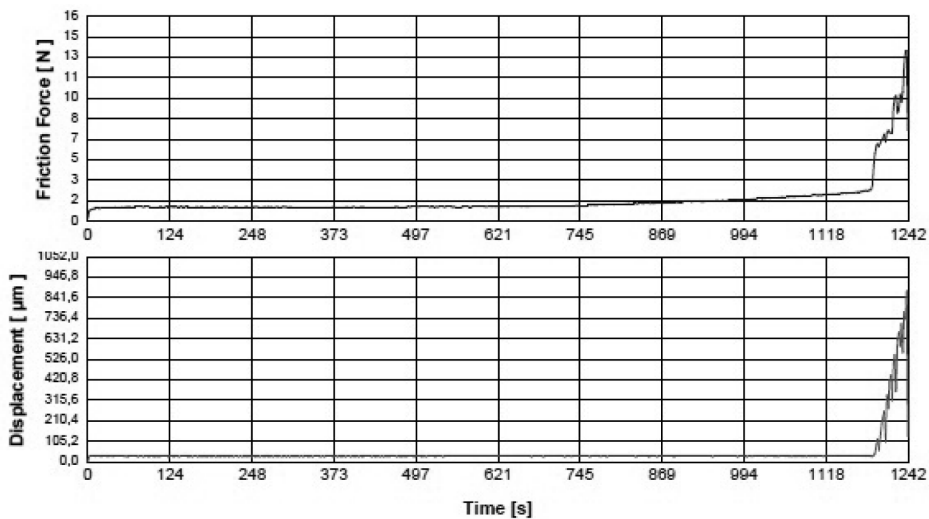


Fig. 3. Examples of friction force and ball displacement charts for Epoxy + 2%SiO₂ material
 Rys. 3. Przykładowe wykresy siły tarcia i zagłębienia kulki w czasie dla materiału Epoxy + 2%SiO₂

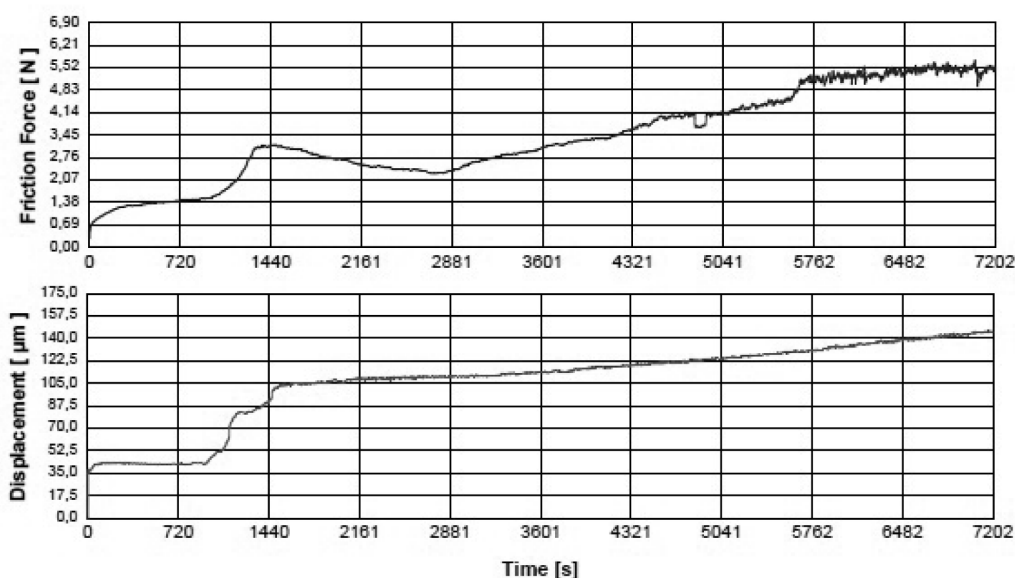


Fig. 4. Examples of friction force and ball displacement charts for 1111 material
 Rys. 4. Przykładowe wykresy siły tarcia i zagłębienia kulki w czasie dla materiału 1111

Figure 6 presents the graph of depth of wear for the materials tested. In this case, one can also see that the wear of F180 and Epoxy materials was the smallest. Samples from Epoxy + 2%SiO₂ were discarded because they seized. On both charts, one can also notice a very large spread of results for the Epoxy + 2% material, which may be caused by the imperfection of the material technology and, consequently, the uneven distribution of the nanofiller in the matrix.

Figure 7 presents a graph of the friction trace width for F180, Epoxy and 1111 materials. Also in this case, it can be seen that the lowest wear was recorded for unmodified epoxy resin and for polyurethane F180. Results for samples of Epoxy + 2%SiO₂ were not shown because they seized.

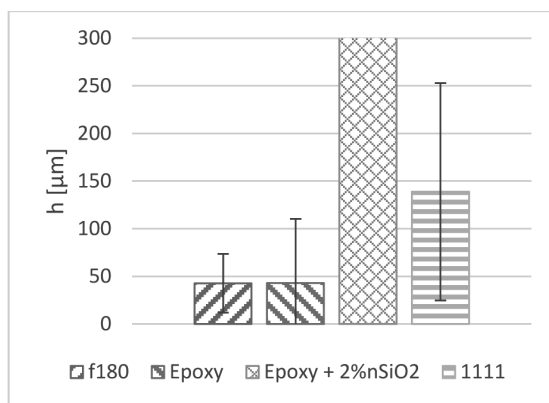


Fig. 6. The depth of wear measured as the maximum ball penetration into the material during the test
 Rys. 6. Głębokość wytarcia mierzona jako maksymalne zagłębienie kulki w materiał podczas badania

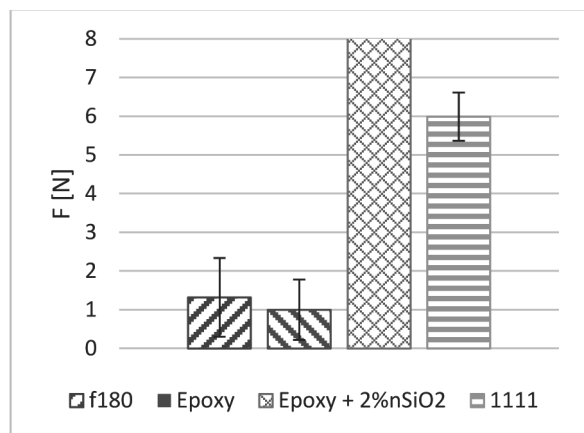


Fig. 5. Maximum friction force of a steel ball on tested materials
 Rys. 5. Maksymalna siła tarcia kulki stalowej o badane materiały

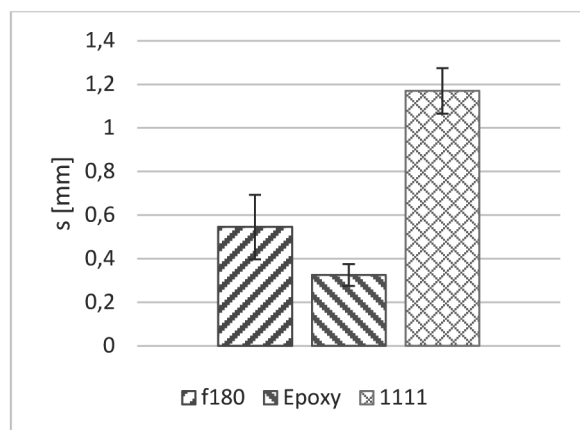


Fig. 7. Friction trace width for F180, Epoxy and 1111 materials
 Rys. 7. Szerokość wytarcia dla materiałów F180, Epoxy i 1111

Figures 8–11 show micrographs of friction traces on samples of F180, Epoxy and 1111 materials. It can be seen that the marks on F180 and 1111 materials are

shallow enough to show the original surface roughness after grinding.

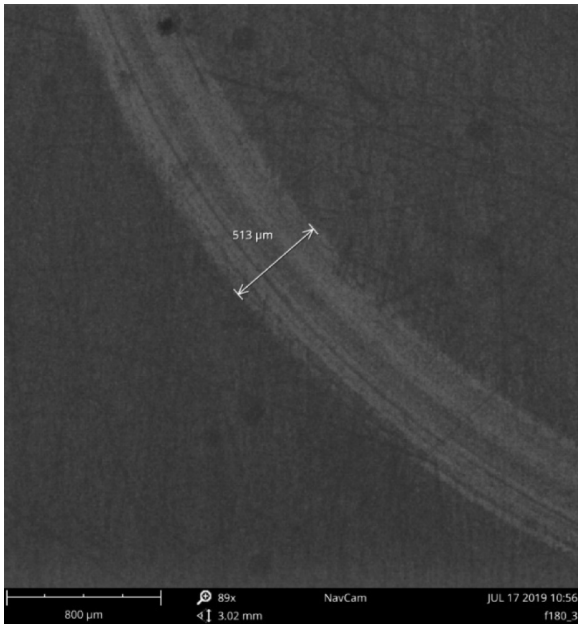


Fig. 8. Micrograph of the friction trace on a sample of F180 material

Rys. 8. Mikrografia wytarcia na próbce z materiału F180



Fig. 9. Epoxy material

Rys. 9. Mikrografia wytarcia na próbce z materiału Epoxy

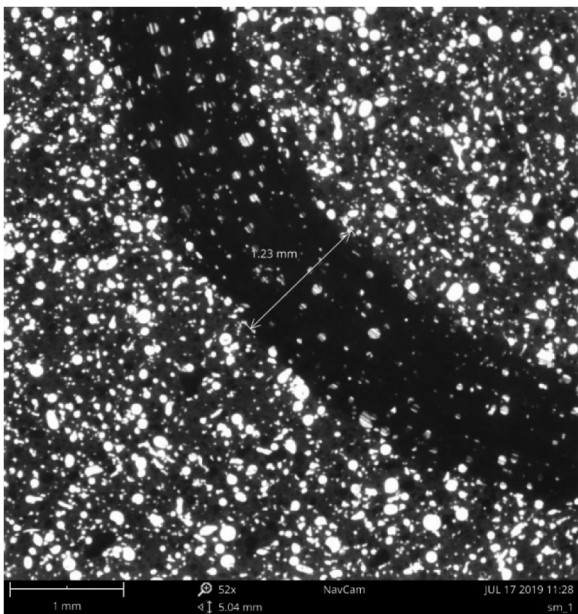


Fig. 10. Micrograph of the friction trace on a sample of 1111 material

Rys. 10. Mikrografia wytarcia na próbce z materiału 1111

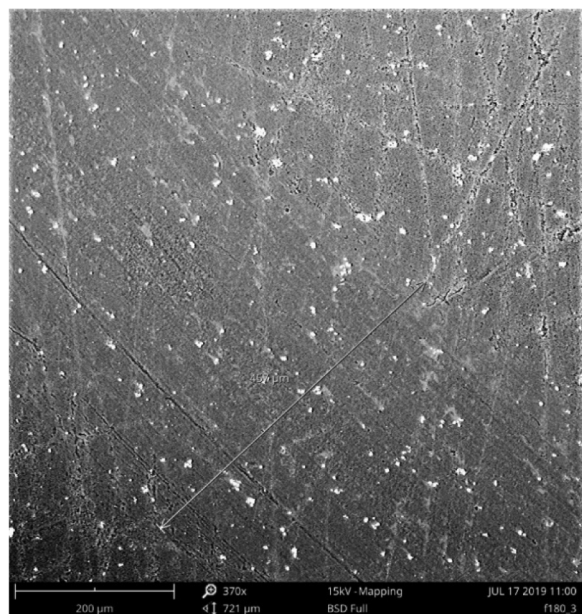


Fig. 11. SEM micrograph of the friction trace on a sample of F180 material

Rys. 11. Mikrografia SEM wytarcia na próbce z materiału F180

DISCUSSION

This paper presents tribological studies of materials that can be used as internal coatings for composite cylinders. Pure epoxy resin and F180 polyurethane showed the best properties. SuperMetal 1111 showed much higher friction force and more wear, while samples from the epoxy-silica nanocomposite seized. Seizure of the nanocomposite could have been caused by irregularities in the manufacturing technology leading to uneven mixing of the filler in the matrix.

In **Figs. 1 and 2**, it can be seen that, for F180 and Epoxy materials, both the friction force and ball displacement remained constant throughout the tests. This may indicate a stable course of material wear processes. For both materials, it can be seen that the process stabilized at the beginning. For the F180 material, however, it lasted longer than for Epoxy, which could be due to the lower hardness of the former. **Figure 3** shows the seizure process of a sample made of nanocomposite. For the first 20 minutes of the test, the

process was stable (however, one can see a progressive increase in friction force) and then abruptly seized. As already mentioned, the probable cause was undispersed filler agglomerates, which are irregularities in the structure at the micro (and even macro) scale. The graph for material 1111 shown in **Fig. 4** shows a highly unstable process of sample wear. Both friction force and ball displacement change irregularly. The material tested was a composite composed of epoxy-novolac matrix and various types of powder fillers of various sizes and geometries. These irregularities in the structure could cause instabilities in the wear process. In addition, after testing, it was noticed that wear beads strongly adhere to the balls. Their adhesion and detachment from the balls during the test could also affect its course.

According to the obtained results, Epoxy and F180 materials were selected for further research on the real object. Work will also be carried out on improving the manufacturing technology for obtaining nanocomposites in an epoxy resin matrix.

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