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WEAR RESISTANCE OF SELECTED ANTI-WEAR COATINGS USED IN MULTI-MATERIAL COMPOSITE HYDRAULIC CYLINDERS

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Abstract. The paper presents tribological tests of selected materials used as liners in a composite hydraulic cylinder. Three coating materials were used for the analysis: Sika F180 polyurethane, Huntsman Araldite LY1564 with Aradur 3487 amine hardener and Bezlona 1111 Super Metal. In addition, uncoated carbon epoxy laminate (CFRP) samples were used as reference material. The instantaneous course of the friction force, its maximum and average value, were the analysed parameters. Ball-on-disk tests were performed on a specialised tester that allows, among other things, to control the operating conditions (clamping force, operating temperature, speed, friction path) and measurement of the instantaneous value of the friction force. After these tests, the friction paths were observed using a Leica DCM8 contactless profilometer with an EPI 20x lens. The amount of energy dissipated due to friction was also determined. The conducted tests and comparative analyses allowed to conclude that the F180 material is the most desirable in terms of tribological properties.

Keywords: composite materials, CFRP, epoxy, polyurethane, hydraulic cylinder, wear, friction.

Introduction

Composite materials are more and more commonly used in mechanical engineering due to a number of advantages, such as low weight, high strength and the possibility of obtaining complicated shapes (Hasan, 2020). They are also widely used in transport, especially in the automotive, aviation and rail industries, allowing to reduce the weight of vehicles and thus reduce fuel demand and improve profitability (Banerjee et al., 2011; Mrazova, 2013). An important feature is that some composite materials are more resistant to fatigue loads during take-off or landing, which results in fewer checks during the operation of the aircraft (Barcikowski et al., 2021). The same expectation applies to all connections: steel and composite (Grzejda et al., 2021). In the aviation industry, the most popular are fibre composites reinforced with glass, carbon or aramid fibres in an epoxy resin matrix. The main areas of their application in airplanes are presented in Figure 1.

Composite materials can also be used to reduce the weight of hydraulic system components such as pipelines (Urbanowicz et al., 2020), accumulators and actuators (Bogdevičius et al., 2021). Despite the good power-to-weight ratio, conventional cylinders in the hydraulic systems are made of steel or are only slightly reinforced with a composite braid (Baragetti & Terranova, 1999; Mantovani, 2020; Marczewska et al., 2006). A further reduction in the share of steel in favour of composite materials would allow a weight reduction of up to 80% while maintaining the current operating parameters (Solazzi, 2021). Therefore, it is becoming extremely important to ensure appropriate tribological cooperation between the piston and the barrel. In the existing solutions, a steel liner is used (a kind of thin-walled pipe) on which composite reinforcement is made. However, it is not an ideal solution from the point of view of weight reduction.

Plastics are widely used in the design of machine components (Skowrońska et al., 2021). Their satisfactory mechanical properties, combined with good tribological properties, self-lubrication and the possibility of modifying the composition, allow them to be used in elements such as gears, pumps and others (Chihai et al., 2019; Krawczyk, 2021; Kujawa et al., 2019; Li et al., 2021; Majdič & Strmčnik, 2019; Zhang et al., 2021). Manufacturing large sliding surfaces, such as the inner surface of a cylinder, from thermoset materials, requires specialised manufacturing methods. Only a few works presenting the manufacturing process and testing the properties of such surfaces have been found in the literature. The described study presents ball-on-disk tests of three materials selected

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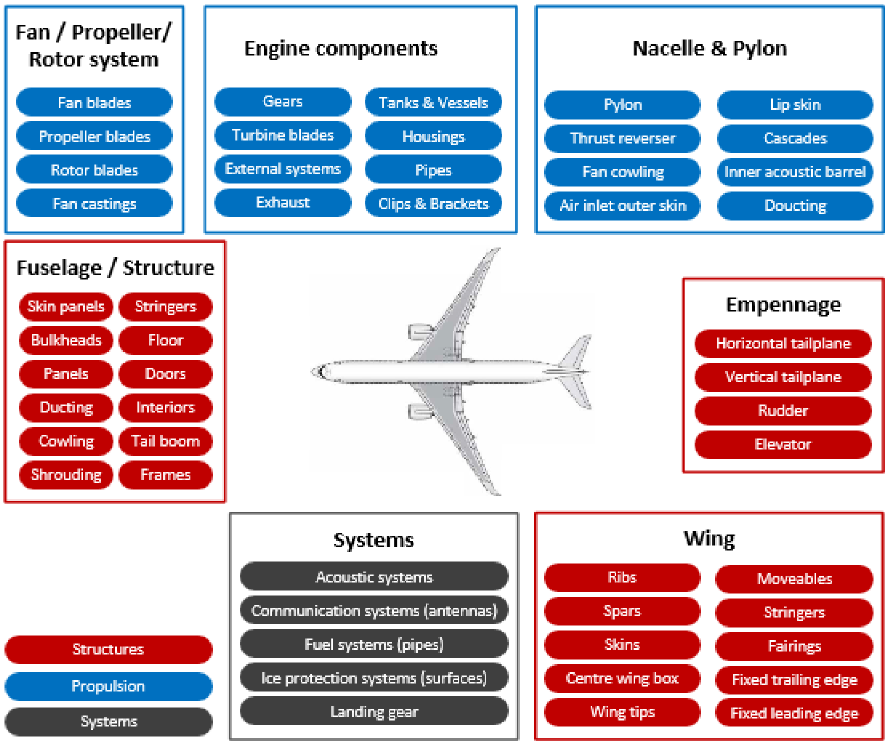


Figure 1. The use of composite materials in the construction of an aircraft
(adopted from Aerospace Technology Institute, 2017)

for the sliding surface of a hydraulic cylinder barrel. The wear and friction results were compared with the reference composite surface. The tested surfaces were applied to composite substrates to better reflect the actual structure of the cylinder material.

The test results will allow the selection of the material used in further research on the real object.

1. Materials and methods

Three materials, which are to be used in multi-material composite hydraulic cylinders, were selected for the tests. Exactly, one of them (the best in the light of the adopted comparative criteria) is to be used for internal anti-wear coatings of the discussed cylinders. An epoxy-carbon laminate, made by vacuum bag method of 8 layers of twill weave carbon fabric and Araldite LY1564 epoxy resin, with the addition of Aradur 3487 hardener, was used as a substrate for the tested materials. On the laminate prepared in this way, coatings of the tested materials were applied. The basic mechanical and thermal properties of the selected materials are presented in Table 1. The first tested material was the Sika F180 two-component polyurethane. The second tested material was Huntsman Araldite LY1564 epoxy resin with Aradur 3487 amine hardener. The third material tested was the commercially available Bezlona 1111 Super Metal. Among many materials, these three were selected due to their availability, ease of processing and promising mechanical and tribological properties. As a reference material, uncoated carbon epoxy laminate (CFRP) samples were tested. The use of such a reference material was to show the purposefulness of using an inner layer made of the selected material.

The tests were carried out in the ball-disk combination. They were aimed at determining the tribological properties of the materials from which the hydraulic system elements were to be made in further work. The test uses disk-shaped samples made of the tested material and counter-samples in the form of balls. The ball is kept motionless and pressed against the sample with a given force. The disk rotates at a given speed, causing friction at the contact with the ball (ASTM International, 2018). The T-11 tribotester manufactured by the Łukasiewicz Research Network – The Institute for Sustainable Technologies in Radom was used. The photograph of the apparatus is shown in Figure 2. This tester allowed to conduct comparative tests of selected materials,

Table 1. Basic mechanical and thermal properties of tested materials

Name	F180	Araldite 1564/3487	Super Metal
Density [g/cm^3]	1.06	1.11	2.5
Shore D hardness	74	N/A	84
Flexural modulus [MPa]	1130	3200	7200
Flexural strength [MPa]	34	130	63
Pot life [min.]	3.5	130–170	15
T_g [^{o}C]	98	83	N/A

Figure 2. Photograph of the T-11 tribotester (ITE PIB Radom, 2007)

which at this stage of the research were in the form of disks with a 1” diameter and 6 mm height. As a counter-sample, Bearing balls made of 100Cr6 steel with a 1/4” diameter were used. The balls were made in 10 accuracy class, and their hardness was 60–62 HRC. The tests were carried out without lubrication. The test parameters were set to correspond as closely as possible to the real conditions for the piston-cylinder pair:

1. Load – 9.81 N,
2. Linear speed – 0.3 m/s (which corresponded to 573 rpm),
3. Friction path – 2160 m (corresponding to a test time of 2 hours),
4. Ambient conditions were controlled and unchanged during all tests (ambient temperature – 21°C).

The remaining parameters were constant for all the tested materials (the same shape of the samples, dry friction, the same friction path, the temperature during the tests was stabilised at 21°C). Each test was repeated a minimum of six times for each material, and the results were statistically processed using the t-Student’s test with a confidence level of 95%. As a result of the tests, the wear determined by the abrasion width and depth was obtained. Additionally, the value of the friction force (maximum and average) and the amount of energy dissipated due to friction were recorded during the tests. After the tests, the wear measurements were carried out at four points (the friction path is a circle; therefore, the wear measurements were made at four points on the circumference, every 90°). Friction path observations were made using the Leica DCM8 contactless profilometer. Measurements were made by a confocal method using Leica Scan 6.5 software and a Leica EPI 20x lens. Post-processing of the results was performed using Leica Map 7.4 software. In addition, friction paths were observed using a Phenom Pro-X Scanning Electron Microscope.

2. Results

Four materials were tested: epoxy, F180, Super Metal and uncoated CFRP. Six samples of each type of material were tested. Figure 3 shows exemplary graphs of the change in friction force during the test – representative examples are presented, and due to the readability of the graph, the confidence intervals have been omitted. The course of the change in the friction force allows us to state that the most promising material (in relation to the CFRP reference material) is F180. The course of the friction force for F180 is characterised by a lower value, the stability of the course without sudden changes. Based on this graph, it is difficult to reject the results obtained for Super Metal because the values of the friction force are similar to the F180. However, a higher initial value of the friction force and its less stable value (significant peaks) put this material in second place. The worst course of friction is visible for epoxy resin. High values of friction force and their large spread resulted in vibrations and noise during the test. Although after about 10 minutes, the process stabilises (after the first stage of friction, a sufficient contact surface is created between the ball and the disk), temporary increases in the average friction force are still visible during further work.

Figure 4 shows the maximum friction force recorded for the tested materials. As shown in Figure 3, the highest values of the friction force for different materials appeared at different times of the test. Most preferably, the peak occurs during the lapping process and then the frictional force is kept constant, lower. Figure 5 shows the average friction force during the test. Comparing both graphs, it can be seen that there is a visible change in the value of the maximum friction force for the tested materials, while the value of the average friction force is very similar. In both graphs, the epoxy resin fares the worst, for which the highest values of the friction force were recorded. The remaining materials show similar results (within the specified confidence interval), and it is difficult to compare

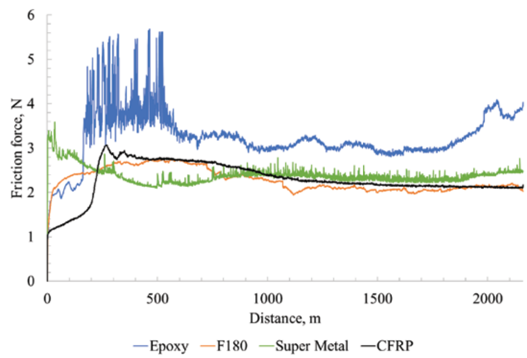


Figure 3. Friction force during the test for tested materials samples

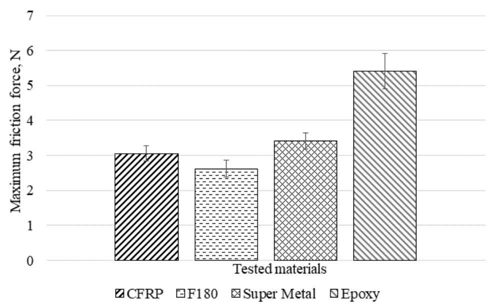


Figure 4. Maximum friction force

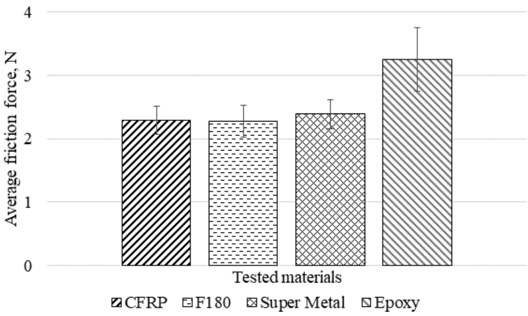


Figure 5. Average friction force

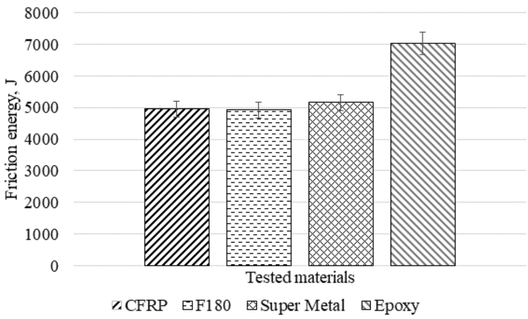


Figure 6. The amount of energy dissipated due to friction during the ball-on-disk test

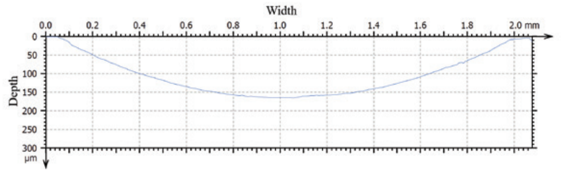
them. When comparing the mean values of the maximum friction forces between the CFRP reference material and the rest of the materials, the difference in the maximum friction force is 77% for epoxy, 11.8% for Super Metal and –14% for F180. Thus, the lowest friction force was recorded for the material F180. However, considering the calculated confidence intervals and assuming the minimum force value for CFRP (2.829 N) and the maximum value for F180 (2.872 N), it cannot be stated unequivocally that the F180 material is better than the uncoated laminate. Comparing the value of the average friction force of epoxy resin to the worst of the remaining materials (Super Metal), it can be seen that the average friction force for epoxy is on average 35% higher.

Figure 6 shows the amount of energy dissipated due to friction determined as the area under the plot of the friction force as a function of displacement (Eq. (1)). The integration was carried out based on the obtained friction force courses. As in Figures 4 and 5, a difference between Epoxy and CFRP can be seen, and it amounts to 42%. The differences between the remaining materials (F180 and Super Metal) and CFRP are insignificant, but within the confidence limits (however, to the benefit of F180, which required the least energy to carry out the process).

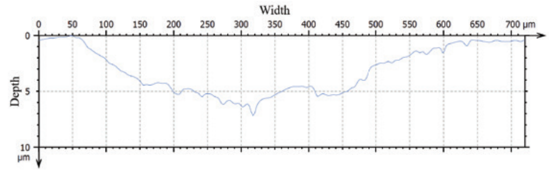
$$E_f = \int_0^T F_f(t) \cdot s(t) dt, \tag{1}$$

where: E_f – energy dissipated due to friction, J; T – test duration, s; F_f – friction force, N; s – displacement, m; t – time, s.

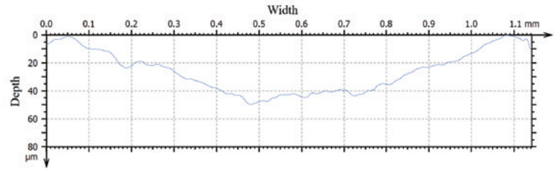
Figure 7 shows sample cross-sections through the friction path, while Figures 8 to 11 show 3D scans of the friction path surface.



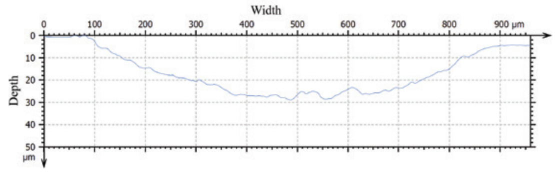
a)



b)



c)



d)

Figure 7. Cross-sections through the friction path for materials: a) Epoxy, b) F180, c) Super Metal, d) CFRP

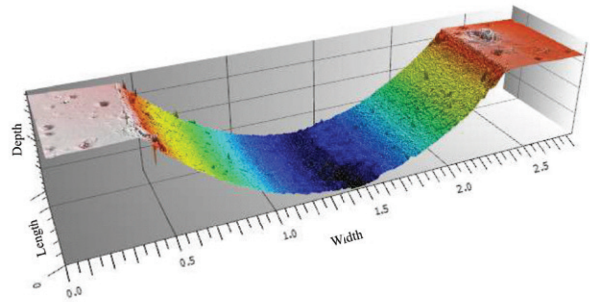


Figure 8. 3D scan of the friction path surface for Epoxy material

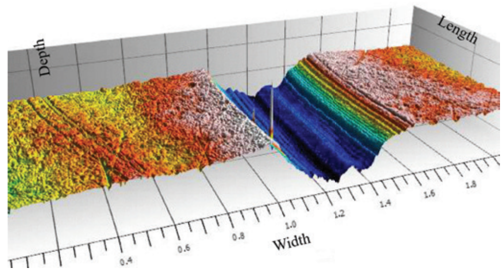


Figure 9. 3D scan of the friction path surface for F180 material

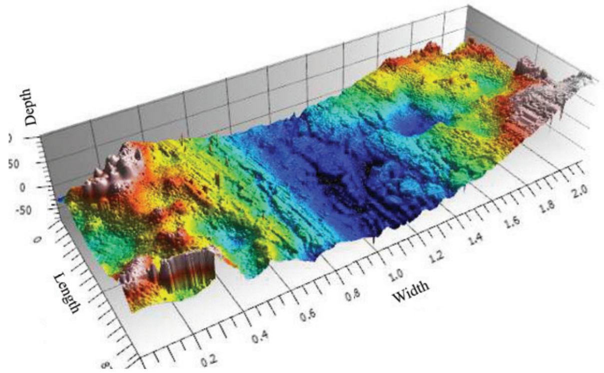


Figure 10. 3D scan of the friction path surface for Super Metal material

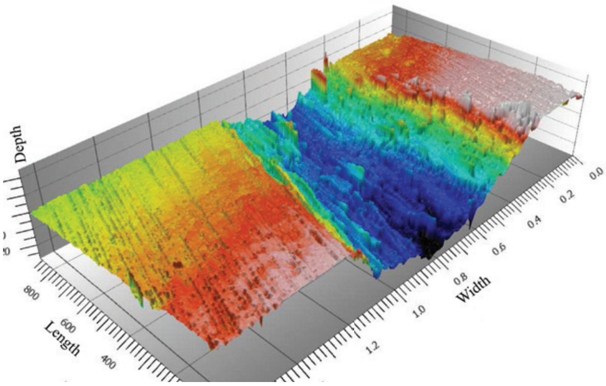


Figure 11. 3D scan of the friction path surface for CFRP material

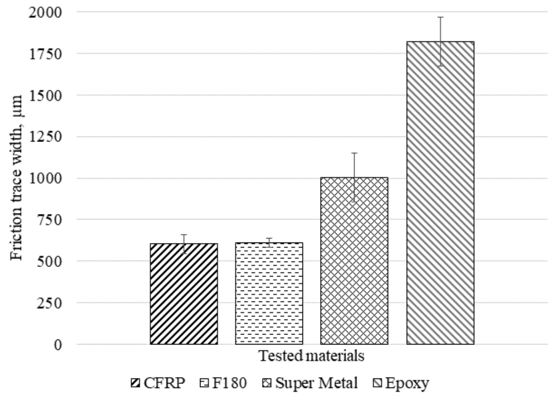


Figure 12. Friction trace width

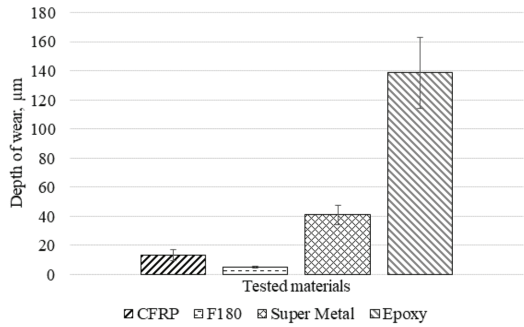


Figure 13. Depth of wear

Figure 12 shows the width of the friction trace for the tested materials, while Figure 13 shows the depth of wear.

Analysing Figures 7–13, i.e. 3D scans, profiles of cross-sections and the depth and width of abrasion marks, it can be seen that epoxy has the worst wear kinetics (it has the highest friction force and the greatest depth and width of the path). At the same time, epoxy is characterised by a very smooth friction path, free of surface defects and microcraters. Presumably, the load applied through the ball has forced a large contact area between the sample and the ball, which will be able to bear the applied load. Consequently, many wear products appeared during the test, which intensified the abrasive wear of the material. Therefore, in the first phase of the tests, such high friction forces and instability of its course were recorded (Figure 3). After creating a sufficient friction surface, the force course was stabilised, and the friction path was smoothed. The lowest wear characterised the material F180 – the width and depth of abrasion are the smallest (this confirms the earlier observations with the previously presented parameters, i.e. friction forces and dissipated energy). As with Epoxy, F180 has a smooth, even surface of friction path. In this case, there is no typical abrasive wear. There is a plastic-elastic deformation of the material that is pushed to the sides of the ball (the ridges adjacent to the groove produced are visible).

The above wear mechanisms are confirmed by the morphology of the wear path carried out by SEM analyses. Sample micrographs of friction paths are shown in Figure 14.

In the case of the surface of Super Metal, cracks, chipping, and even detachment of pieces of material can be noticed, leading to the deterioration of tribological properties (Figures 6, 10, 14b). Both the friction force and the amount of energy dissipated due to friction for this material were comparable with the values obtained for the reference material (CFRP) and F180. However, the width and depth of the abrasion are greater (Figure 12 and 13). Similar, although smaller, chipping can be observed on the surface of the CFRP material. Figure 14d clearly shows the need to use anti-wear coatings on an uncoated carbon-epoxy laminate due to the tearing off of large fragments of the laminate (especially when placed perpendicular to the direction of movement). For CFRP, however, the friction force and wear were only slightly greater than for the F180. It is not without significance that the tear-off elements of the laminate with the hydraulic oil are distributed throughout the entire hydraulic system. In particular, they get to the hydraulic components that are sensitive to contamination, such as servo valves or multi-piston pumps. This can lead to their critical damage.

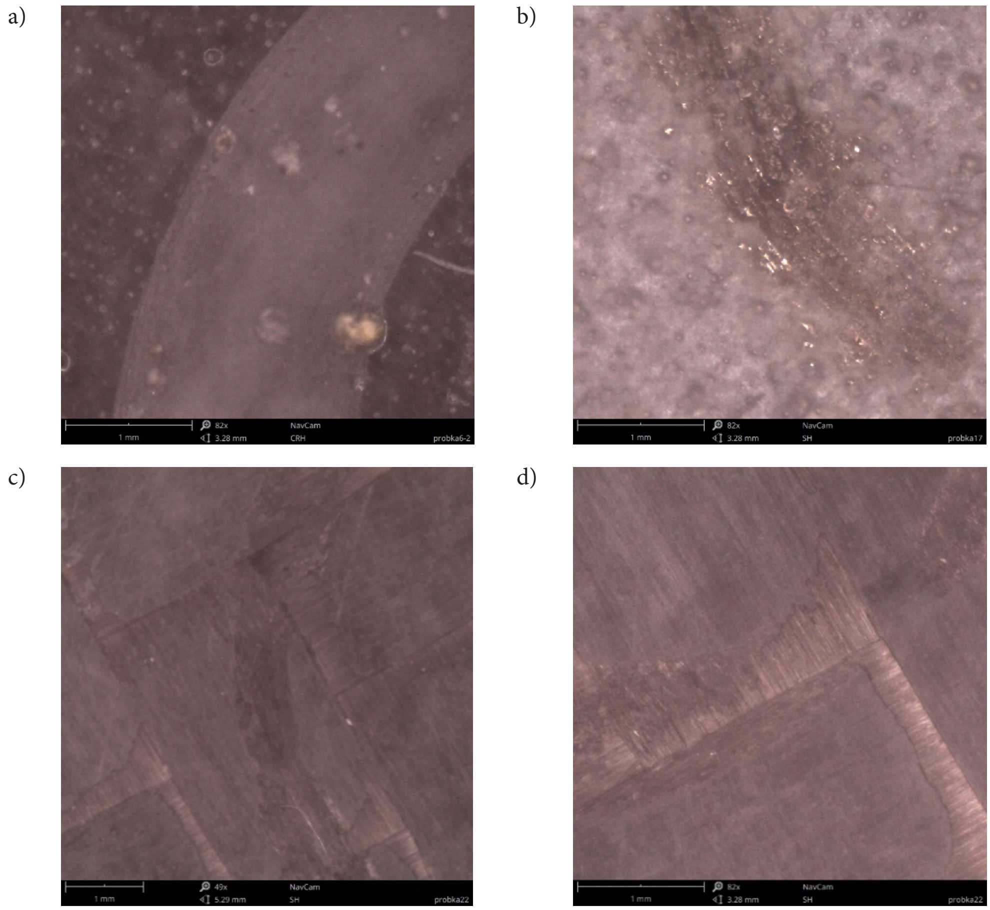


Figure 14. Sample micrographs of abrasions on a material sample: a) epoxy, b) Super Metal, c) and d) CFRP

In all cases, the tribological wear is additionally aggravated by the fatigue interactions at the sliding contact. A ball sliding on the surface at any given moment makes contact with the coating, similar to rolling a ball or a roller. Compressive stresses occur in front of the ball, tensile stresses occur behind the contact zone, reaching very high values due to the stress concentration. This phenomenon causes a continuous deformation of the coating-substrate system with a frequency dependent on the rotational speed.

Conclusions

The paper presents ball on disk tests of three materials potentially qualifying as materials for internal coatings in a composite hydraulic cylinder and a test of one reference material. A wear analysis was also carried out using a non-contact profilometer.

The main novelty of the presented research is the analysis of the possibility of using new materials as a liner material for composite hydraulic cylinders.

The material with the best tribological properties turned out to be F180 polyurethane, which will be used to produce the cylinder prototype. It was characterised by the lowest wear and the lowest values of friction force and the amount of energy dissipated due to friction. The highest values were achieved by epoxy, which disqualifies it as a sliding coating. Also, Super Metal material was characterised by significantly higher wear and friction force values than F180. Despite the good results obtained for CFRP material, it cannot be used due to pressure-loaded composite parts' weepage effect. Wear products resulting from friction should be considered an important criterion for assessing the suitability of the proposed material. It was indicated that for CFRP material, the resulting wear products might be transported to other distant elements of the hydraulic system and cause their failure. The resulting additional contamination of the working fluid is particularly dangerous in the high-pressure and micro-hydraulic systems used in aircraft. Hydrotronic components, such as the latest generation of proportional directional control valves and servovalves, are also exposed to this type of contamination (≤2 μm). Already, about 80% of all hydraulic systems failures are caused by contamination of the working fluid, and further contamination will increase the failure rate of these systems. An important step in subsequent studies is to consider the specific environmental conditions of the cooperation of rubbing materials. It is planned to perform tests for samples immersed in hydraulic oil at a different, stabilised temperature. Moreover, in the process of reducing the mass of the hydraulic cylinder, the reduction of the mass of the cylinder heads and optimisation of their shape play an important role.

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Author contributions

Conceptualization and methodology: TL, ML and MS; investigation: TL and ML; resources: MS; data curation: JK; writing – original draft preparation: ML; writing – review and editing: JK; visualization: ML and TL; supervision: MS. All authors have read and agreed to the published version of the manuscript.

Disclosure statement

The authors declare no conflict of interest.

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