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CONCEPT FOR AN ADVANCED TRIBOLOGICAL SYSTEMS RESEARCH METHODOLOGY

KONCEPCJA METODYKI BADAŃ ZAAWANSOWANYCH SYSTEMÓW TRIBOLOGICZNYCH

Key words: tribological system, geometric structure of the surface, functional properties, research methodology.

Abstract: The conduct of research on advanced tribological systems in order to determine the best solutions in terms of the durability and reliability of technical objects containing these systems requires a multifaceted and comprehensive approach due to the complexity of tribological processes occurring during operation. Observation of these processes is complicated and limited due to the inaccessibility of the friction zone. Therefore, progress in improving tribological characteristics is mainly determined by developing laboratory test methods.

From the point of view of describing the tribological properties of the surface layer, the geometric structure of the surface (shape, waviness, roughness and surface defects), the structure of the physicochemical zones (microstructure, mechanical properties, physicochemical properties), and the ability to properly interact with the lubricant should be taken into account. Studies of advanced tribological systems should therefore include two complementary test methods, i.e., friction wear tests and surface layer tests (as manufactured and as operated).

This paper presents a concept for research on advanced tribological systems and a justification for conducting complementary research on these systems, referring to selected examples (processing tools, joint implants, and dental implants). The research results are examples which illustrate the essence of conducting complementary research.

Słowa kluczowe: system tribologiczny, struktura geometryczna powierzchni, właściwości funkcjonalne, metodyka badań.

Streszczenie: Prowadzenie badań zaawansowanych systemów tribologicznych w celu określenia najlepszych rozwiązań pod względem trwałości i niezawodności obiektów technicznych zawierających te systemy wymaga wielowątkowego i kompleksowego podejścia ze względu na złożoność procesów tribologicznych zachodzących podczas eksploatacji. Obserwacja tych procesów jest skomplikowana oraz ograniczona z uwagi na niedostępność strefy tarcia. Dlatego postęp w poprawianiu charakterystyk tribologicznych determinowany jest głównie przez rozwój metod badań laboratoryjnych.

Z punktu widzenia opisu właściwości tribologicznych warstwy wierzchniej należy brać pod uwagę zarówno strukturę geometryczną powierzchni (kształt, falistość, chropowatość i wady powierzchni), strukturę fizykochemicznych stref (mikrostruktura, właściwości mechaniczne, właściwości fizykochemiczne) oraz zdolność do właściwej interakcji ze środkiem smarowym. Badania zaawansowanych systemów tribologicznych powinny zatem obejmować dwie komplementarne metody badawcze, tj. badania tarciowo-zużyciowe oraz badania warstwy wierzchniej (wytworzonej i eksploatowanej).

W pracy przedstawiono koncepcję badań zaawansowanych systemów tribologicznych oraz zasadność prowadzenia komplementarnych badań tych systemów, odnosząc się do wybranych przykładów (narzędzia obróbcze, implanty stawów, implanty stomatologiczne). Wyniki badań stanowią przykłady pokazujące istotę prowadzenia badań komplementarnych.

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INTRODUCTION

The durability of the tribological system depends on many factors **[L. 1]**, including the materials used for the components of the system, the geometry and shaping of the surface of frictional components in the technological process, the conditions of environmental cooperation, kinematics, dynamics, time and factors accompanying and interfering with the efficient functioning of the system (including wear mechanisms, wear products) – **Figure 1**.

The conduct of effective research on tribological systems in order to determine the best solutions in terms of the durability and reliability of technical objects (machines and devices) containing these systems requires a multifaceted approach and the use of complementary research methods. Observation of tribological processes during operation is complicated and limited due to the inaccessibility of the friction zone **[L. 1, 2, 3]**. Therefore, progress in improving tribological characteristics is determined mainly by developing laboratory test methods, including the intensive development of research methods **[L. 4]**, enabling correct characterisation of the surface layer.

From the point of view of the description of the tribological properties of the surface layer, both the nature of the surface shape (geometric surface structure – shape, waviness, roughness and surface defects) as well as functional properties, including resistance to tribological wear, fatigue strength, and ability to properly interact with the lubricant should be taken into account. Studies of advanced tribological systems should therefore include two complementary test methods **[L. 4]**, i.e., friction wear tests and surface layer tests (as manufactured and as operated). Applying a comprehensive approach to studying advanced tribological systems requires the cooperation of scientists from different fields of science; therefore, it is important to create research teams that will solve complex and interdisciplinary scientific problems. Solving these scientific problems also requires the establishment of cooperation with various external, national and foreign entities (universities, research institutes, enterprises) where research is carried out using complementary research infrastructure and the analysed results.

This paper presents a general concept for a methodology of researching advanced tribological systems, referring the details of the concept to two independent cases – technological (a tool-workpiece interface) and operational (the head-bearing of an orthopaedic system and the tooth-tooth interface of a dental system).

In terms of machining, it is possible to distinguish a physically dry friction zone (contact between the physically clean surfaces of the tool and the workpiece) and a technically dry friction zone. The friction coefficient is determined by the cutting tool blade's mechanical, structural and physicochemical properties and workpiece. When introducing a lubricating medium (such as a cooling and lubricating liquid into the processing zone), there is a change in the tribological state; additionally, there is a mixed friction zone and a liquid friction zone. Research in this area may include, among other things, testing materials in terms of minimising the wear of the cutting tool (cutting tool blade) and the accuracy of the machined surface shape. The wear of the tool is related to the loss of functional properties of the surface

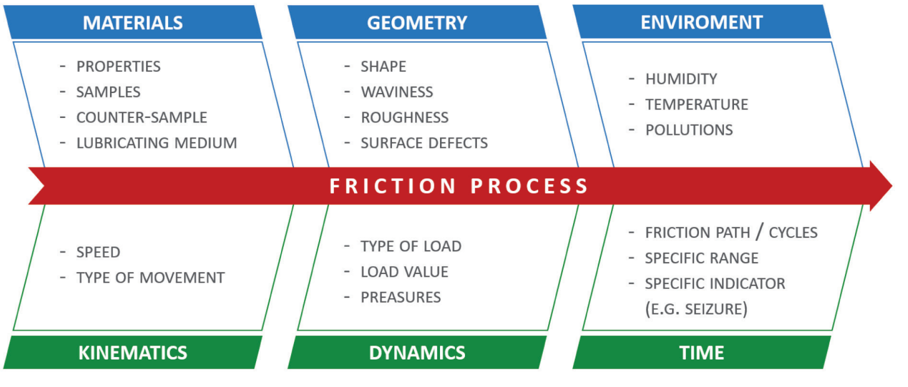


Fig. 1. Cause and effect diagram: factors influencing the friction process and its effects [L. 4]
Rys. 1. Diagram przyczynowo-skutkowy: czynniki wpływające na proces tarcia i jego skutki **[L. 4]**

layer (assumed by the technical documentation of the machining capability), which has a direct impact on the nature of shaping the surface of the workpiece and the quality of production. Examples of published research in this area are works dealing with the issues of the impact of technological processes and tools on shaping the surface of the workpiece **[L. 5**, **6**, **7]** and the impact of machining conditions on the wear of the cutting tool **[L. 8**, **9]**. While it is possible to monitor the quality of workmanship (parametric and non-parametric analysis) and thus assess the technological process used, such monitoring does not necessarily occur in a tool. Problems that occur with the quality of workmanship (e.g., non-compliance with the technical documentation) trigger the procedure of analysis of machining operations and parameters as well as the tools used and their condition. Minor, often unnoticeable damage to the primary tools over time generates secondary damage and consequently leads to a deterioration of the quality of the workpieces and economic losses. Therefore, research on the selection of materials for tools that will ensure appropriate durability and reliability of tools in the technological process is important.

Due to the unresolved problem of the durability of artificial joints, including the hip joint, there is a need to search for both material and technological solutions in the field of shaping the functional (tribological) properties of the surface layer of frictional components. Thus, it is important to conduct research on both new biomaterials (ceramic and titanium) for components of long-term implants (simple model research) as well as prototype components produced (complex simulation research) in order to solve the problem of the durability of artificial joints. Assuming the cooperation of the femoral head component with the polymeric acetabulum, the component affected by degradation is the polymeric acetabulum, hence the responsibility for the durability of the system with the friction pair of the head-shell lies on the side of the head and the very nature of the shape's surface and head cooperating with the surface of the acetabulum.

Model tests on elements with simple geometry (plates, balls, blocks, etc.) allow for determining the functional properties of materials and selecting materials for frictional components **[L. 10–12]**. On their basis, prototype elements are created and tested in conditions reflecting the actual operating conditions of a given tribological system **[L. 13**, **14]**. However, it should be remembered that laboratory tests do not fully reflect the functioning of the human body, as parameters describing the activity and lifestyle of the user are difficult to predict. Nevertheless, it is important to conduct laboratory tests to search for the best material and construction solutions to minimise wear, energy use, and wear by-products that have a negative impact on the human body during use.

One problem in the field of dental issues is bruxism, which is a biological risk factor for complications around dental implants, as well as a risk factor for mechanical complications. Due to the growing problem of bruxism, research on dental materials in conditions reflecting the jaw system (relative displacement of teeth) of a patient clenching teeth and/or grinding teeth is becoming more important. Composite materials are invaluable in dental applications, including the restorative treatment of teeth with pathological abrasion caused by bruxism or erosion. Composite materials, as long as they are resistant to erosion factors, do not exhibit such resistance to tooth clenching and/or grinding, which may lead to their degradation over time. Therefore, there is a need for advanced materials tests in dental applications with high abrasion resistance. In order to search for the best material solutions for use in patients with pathological abrasion caused by bruxism, such research should be conducted in specially developed tribological systems that will ensure the possibility of setting different conditions due to the very broad range of functions in real conditions, as emphasised in the paper **[L. 15]**.

Published works in this area cover issues related to the study of new materials and functional (tribological) properties of materials used in dental practice **[L. 16–20]**.

Currently, scientific research on tribological systems is carried out to a limited extent, which does not allow the phenomena and physical processes occurring in the kinematic node and affecting the mechanism of wear of friction elements to be explained. Scientific research focuses on determining the impact of the material and production technology on tribological characteristics or on determining the impact of tribological test conditions and tribological characteristics on the amount of wear of the elements in frictional contact (the most common studies of traces and wear products using SEM/EDS).

Regardless of the type of the above-mentioned problem, it is important to pay attention to the adoption of an appropriate methodology for testing tribological systems based on a comprehensive approach, including both friction and wear tests as well as surface shaping (stereometry) tests. Therefore, this article presents a general concept for a research methodology (in particular, attention was paid to the use of research devices of the geometric structure of the surface) which may be helpful in characterising advanced tribological systems.

MATERIALS AND METHODOLOGY CONCEPT

Due to the problem of the issue in question, the research subject is special purpose materials, namely materials used in machining tools and as components of biotribological systems. Such materials should and are characterised by high material (mechanical) properties. In addition to the need to meet high requirements in terms of material properties, functional and tribological properties are also important. Due to their connection with the technological process, Tribological characteristics depend, among other things, on the surface shape of the frictional components **[L. 4]**.

Thus, the concept of the methodology for testing tribological systems should include both the shaping of the surface of frictional components in the technological process, as well as friction and wear tests carried out under appropriate conditions, including models, simulations, and ultimately real-life conditions. Surface shaping tests should also include surface shaping in the operation process and wear mechanism tests (including wear marks and wear by-products).

The concept for advanced research of tribological systems is presented in **Figure 2**. After analysing the literature in terms of the issue constituting this research problem, it is necessary to develop subsequent stages of research and analysis (taking into account the technological process and materials and their properties) that will allow the

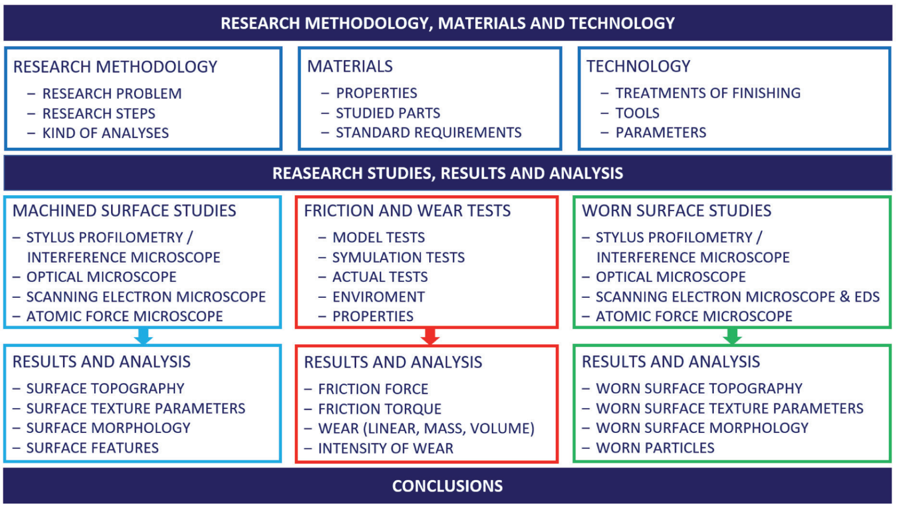


Fig. 2. A concept for testing tribological systems
Rys. 2. Koncepcja badań systemów tribologicznych

defined problem to be solved. As part of the test methods, apart from dedicated devices for friction and wear tests (tribotesters), devices for testing the geometric structure of the surface should be mentioned. In this respect, attention should mainly be focused on those elements of the geometric structure of the surface that play an important role in the friction and wear process, i.e., surface defects, waviness, and roughness **[L. 4, 21]**. The devices used should provide comprehensive surface shaping characteristics, including non-parametric (qualitative) and parametric (quantitative) analysis. These may be optical microscopes (OM), scanning electron microscopes (SEM, including EDS microscopes), atomic force microscopes (AFM), and other stereometric research methods (SRM) such as confocal or interference microscopes, etc.

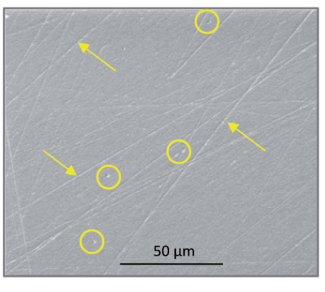
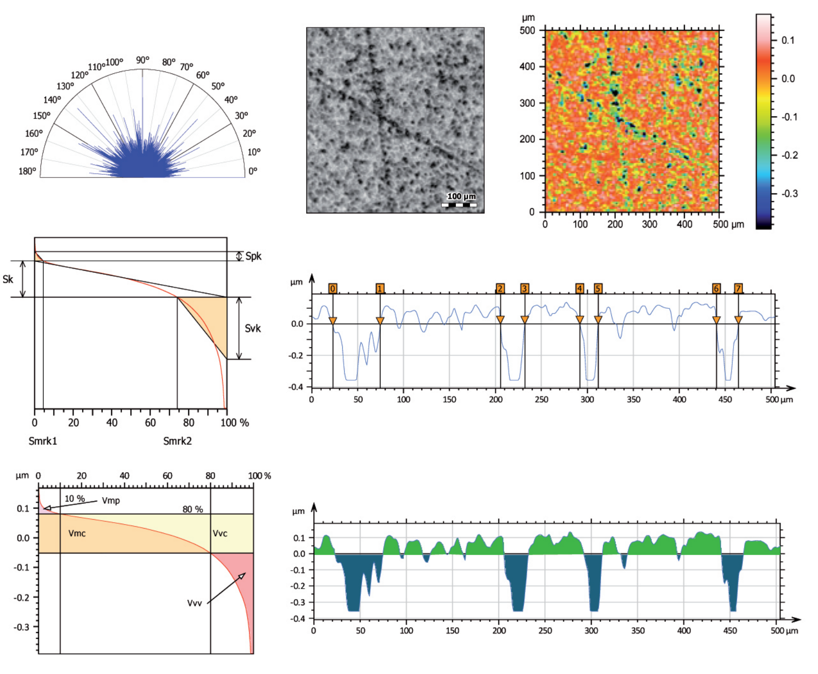
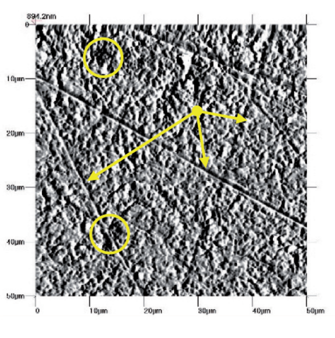
The research stages and examples of results are presented in the next paragraph. The research results concern ceramic materials based on zirconium dioxide and aim to show what information can be obtained by applying the adopted testing and analysis methodology to any tribological system.

CONCEPT METHODOLOGY – DESCRIPTION AND RESEARCH EXAMPLES

Tests of the geometric structure of the surface shaped in the technological process concern the selection of materials and their properties as well as the technological process of manufacturing frictional components, in particular techniques for shaping the technological surface layer and for ensuring appropriate material microstructure, mechanical and physicochemical properties and geometric structure of the surface layer. The purpose of research carried out in this area is to check the compliance of the surface shape of frictional components with the guidelines (documentation, standard, etc.) related to the final purpose of the tested elements and to determine the potential functional properties of the surfaces of frictional components. Sample results (images – surface morphology/surface topography, and parameters – surface texture parameters) are given in **Table 1**.

The verification of the surface characteristics of the surface layer obtained in the technological process takes place during the operation process, as

Table 1. Sample test results of the geometric structure of the surface produced
Tabela 1. Przykładowe wyniki badań struktury geometrycznej/ukształtowania powierzchni wytworzonej

<table>
<tr><th colspan="2">Research methods</th></tr>
<tr><th>SEM</th><th>SRM – non-parametric and parametric descriptions</th></tr>
<tr><td></td><td rowspan="3"></td></tr>
<tr><th>AFM</th></tr>
<tr><td rowspan="2"></td></tr>
<tr><td>ISO 25178: Sa, Sq, Sz, Sp, Sv, Ssk, Sku, Sal, Str, Std, Sdq, Sdr, Spd, etc.
ISO 4287: Ra, Rq, Rz, Rp, Rv, Rsk, Rku, etc.</td></tr>
<tr><th colspan="2">Scope of analysis and inference</th></tr>
<tr><td colspan="2">Non-parametric description (based on graphs, surface maps and photos) and parametric description (based on 2D and 3D parameters) of the shaping of the machined surface. Checking the compliance of the manufactured item with the requirements and determining the machined surface's potential functional properties and the possible impact on the frictional component in the friction node of a given tribological system.</td></tr>
</table>

part of which the technical object performs the tasks for which it was designed and manufactured, hence the area *Friction and wear tests* (transformation of the surface produced into the surface in operation). The purpose of the research conducted in this area is to determine the relationship between the functional properties of the technological surface layer and tribological characteristics (including the friction coefficient and the intensity of wear). The obtained results of tribological tests carried out for various tribological systems should refer to the test conditions, i.e., to test methods (model, simulation or actual), materials used for frictional components, the geometry of tribological node elements, friction parameters, characteristics of the technological surface of the surface layer of friction elements, environment, etc. Examples of results (tribological characteristics) are given in **Table 2**.

After determining the relationship between the shape characteristics of the technological surface of the top layer and tribological characteristics, it is additionally necessary to determine the shape characteristics of the surface layer and identify the wear mechanisms of the components of the tested tribological systems, which – in the case of tests – constitutes the area *Tests of the geometric structure of surfaces shaped in the process of operation*. The research carried out in this area aims to identify the relationship between the obtained tribological characteristics as part of friction and wear tests and the characteristics of the surface layer and wear mechanisms. Sample results (images – surface morphology/surface topography and parameters – surface texture parameters) are given in **Table 3**.

The results obtained within the third area – *Tests of the surface shaped in the process of operation*

Table 2. Sample results of friction and wear tests – tribological characteristics
Tabela 2. Przykładowe wyniki badań tarciowo-zużyciowych – charakterystyki tribologiczne

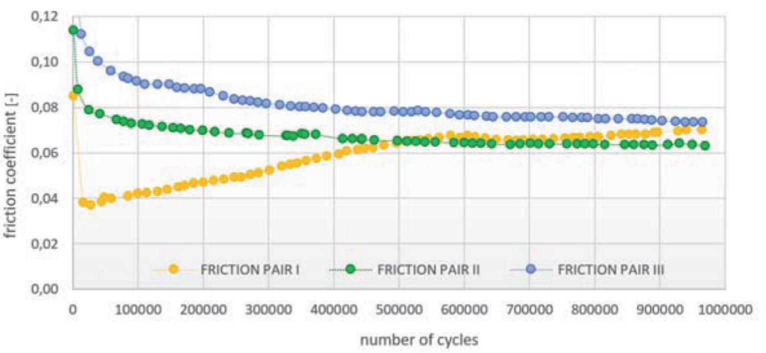
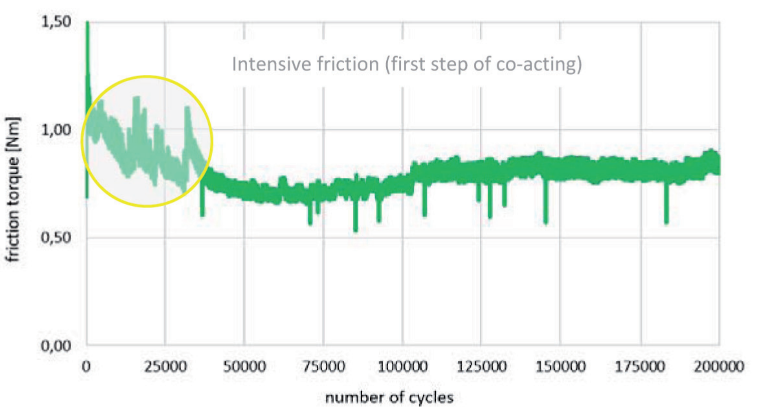
<table>
<tr><th>Friction and wear tests methods</th><th>What is tested?</th></tr>
<tr><td>Model tests</td><td rowspan="2">Tribological characteristics –
the friction coefficient,
the wear linear/mass/volumetric),
the intensity of wear.</td></tr>
<tr><td>
</td></tr>
<tr><td>Simulation/actual tests</td><td rowspan="2">Tribological characteristics –
the friction torque,
the wear linear/mass/volumetric),
the intensity of wear.</td></tr>
<tr><td>
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Table 3. Sample test results of the geometric structure of the surface in operation
Tabela 3. Przykładowe wyniki badań struktury geometrycznej/ukształtowania powierzchni eksploatowanej

<table>
<tr><th colspan="2">Research methods</th></tr>
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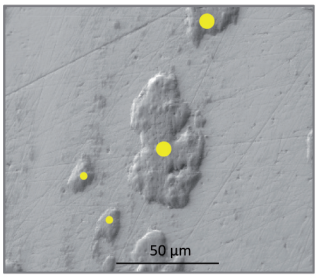
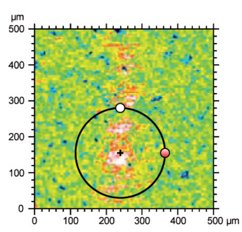
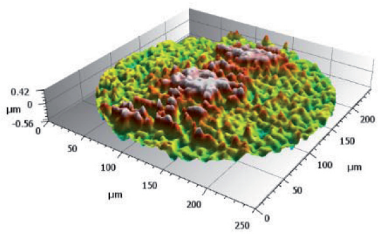
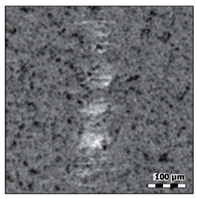
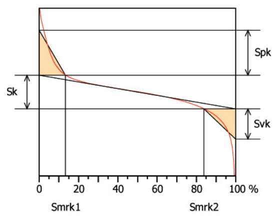
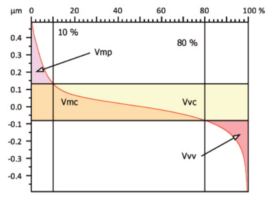
<tr><td>
</td><td rowspan="3">



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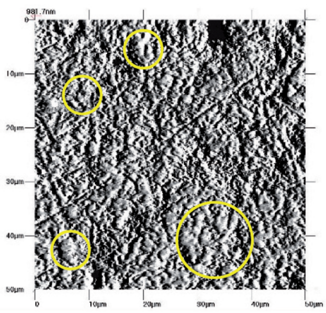
<tr><th>AFM</th></tr>
<tr><td rowspan="3"></td></tr>
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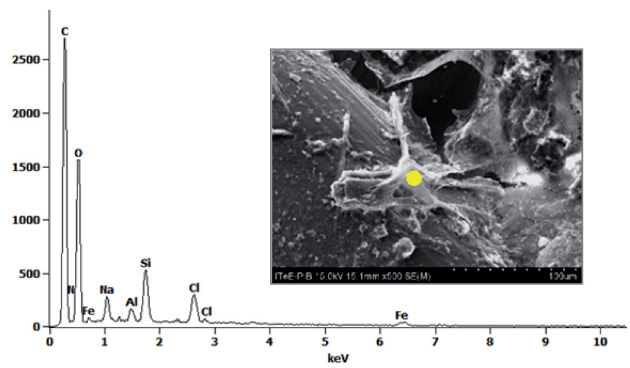
<tr><th>EDS</th></tr>
<tr><th>OM</th><td rowspan="2">
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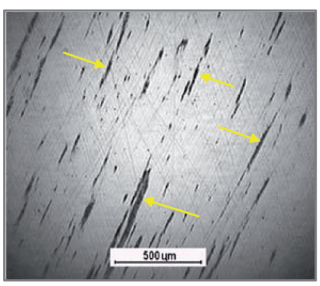
<tr><td>
</td></tr>
<tr><th colspan="2">Scope of analysis and inference</th></tr>
<tr><td colspan="2">Non-parametric description (based on graphs, surface maps and photos) and parametric description (based on 2D and 3D parameters) of the shaping of the surface in operation. Determination of the degree of wear of the elements of a given tribological system. Identification of the wear mechanism and by-products (qualitative and quantitative analysis).</td></tr>
</table>

affect the approach to the issues of the first area – *Tests of the geometric structure of the surface shaped in the technological process*, which is a comprehensive approach to solving the problems of shaping the technological and operational surface layer of the frictional components of the tribological system and the related durability of tribological systems and the reliability of technical objects (machines and devices) containing them. Thanks to this, it is possible to improve the technological process and thus monitor the quality of manufactured objects, thus affecting the durability and reliability of the tribological system.

CONCLUSIONS

The presented concept for a research methodology aims at encouraging researchers to conduct both comprehensive research (geometric structure of the manufactured surface and the surface in operation and tribological characteristics) as well as complementary research (use of equal measuring devices in tests of the geometric structure of the surface and friction and wear tests).

Examples of research results, presented in tabular form, show what selected information can be obtained using various devices, what can be inferred from this information, and what further steps need to be taken to solve the research problem related to a specific tribological system.

In the next step, the authors plan to publish the results of research obtained using the proposed methodology for testing tribological systems in relation to new solutions of composite materials used in the dental restoration treatment of patients suffering from pathological abrasion caused by bruxism and erosion.

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