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CONCEPT FOR A RESEARCH METHODOLOGY OF SURFACE TOPOGRAPHY – TESTING AND ANALYSIS OF TRIBOLOGICAL WEAR TRACES

KONCEPCJA METODYKI BADAŃ TOPOGRAFII POWIERZCHNI – BADANIE I ANALIZA TRIBOLOGICZNYCH ŚLADÓW ZUŻYCIA

Key words: tribological wear, wear mechanism, wear traces, surface topography, research methodology.

Abstract: The methodology of surface topography research plays a key role in identifying and describing the wear mechanism, including the tribological wear traces. In the published literature, wear traces are most often described based on the surface morphology created in the operation process (microscopic image – optical microscope OM, scanning electron microscope SEM, atomic force microscope AFM); less frequently used are 2D profile description (contact or non-contact profilometer) or 3D topography (profilometer, confocal microscope, interference microscope, focus variation microscope). Each method of testing the worn surface has its own characteristics and purposefulness of use. The combination of different methods enables a comprehensive assessment of the surface topography created in the operation process and the characterisation of tribological wear traces.

This work presents the main issues in the range of research methodology of the surface topography created in the operation process (operated/worn surface topography) – the purpose of research, research programme, research methods and tools, analysis of research results (quantitative – parametric and qualitative – non-parametric). The research methodology of the surface topography and tribological wear traces is presented on selected examples. The method of conducting a comprehensive analysis, including all elements – surface morphology, 2D profile analysis and 3D topographic analysis – is discussed.

Słowa kluczowe: zużycie tribologiczne, mechanizm zużycia, ślady zużycia, topografia powierzchni, metodyka badań.

Streszczenie: Metodyka badań topografii powierzchni odgrywa kluczową rolę w identyfikowaniu i opisie mechanizmów zużycia, w tym śladów zużycia tribologicznego. W publikowanych pracach najczęściej identyfikacja śladów zużycia przeprowadzana jest na podstawie morfologii powierzchni eksploatowanej (obraz mikroskopowy – mikroskop optyczny OM, skaningowy mikroskop elektronowy SEM, mikroskop sił atomowych AFM), rzadziej stosowane są opisy profilu 2D (profilometr stykowy lub bezstykowy) czy topografii 3D (mikroskop konfokalny, mikroskop interferencyjny, mikroskop różnicowania ogniskowego). Każda z metod badań powierzchni eksploatowanej ma swoją charakterystykę oraz celowość zastosowania. Połączenie różnych metod umożliwia kompleksową ocenę powierzchni eksploatowanej oraz charakterystykę śladów zużycia tribologicznego.

W niniejszym opracowaniu przedstawiono główne zagadnienia w zakresie metodyki badań powierzchni eksploatowanej – cel badań, program badań, metody i narzędzia badawcze, analiza wyników badań (ilościowa – parametryczna oraz jakościowa – nieparametryczna). Metodykę badań powierzchni eksploatowanej i śladów zużycia tribologicznego zaprezentowano na wybranych przykładach. Omówiono sposób przeprowadzenia kompleksowej analizy, obejmującej wszystkie elementy – morfologię powierzchni, analizę profilową 2D oraz analizę topograficzną 3D.

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INTRODUCTION

Conducting effective tests of tribological systems has to determine the best solutions in terms of the durability and reliability of technical objects (machines and devices) containing these systems. This requires a multithreaded approach, including the use of complementary research methods, which have been described, among others, in work **[L. 1]**. It is similar in the case of tests aimed at identifying wear mechanisms and characteristics of operating surfaces, including wear traces of the friction elements of the tribological system.

In the operation process, under the influence of friction, external extortions and the time of their impact, the surface layer formed in the technological process is modified in stereometrics, physical and chemical terms. The operation process is intermittent, taking place in changing environmental conditions. At each stage, the surface layer changes, modifying the functional properties of the operating surface of the friction elements. Under real conditions, it is impossible to control the degree of wear of the friction elements (the friction zone is inaccessible) without disassembling and assembling the tribological system's friction node. Wear is usually assessed after the end of the operation or in the event of detecting functional irregularities (damage to the machine, wear of components). Tests of the surface layer, the properties of which are modified during the operation process, can be carried out in laboratory conditions **[L. 2]**. It should be emphasised that there is a discrepancy between the characteristics of the surface layer obtained in laboratory conditions and the characteristics of the surface layer obtained in the actual operating conditions of the technical object. For this reason, it is important to perform as many qualitative and quantitative analyses and descriptions as possible relating to the surface modified in the operation process. This applies both to the identification of the wear mechanism as well as to the characterisation of the wear trace and surface topography. For this purpose, it is possible to use various measuring instruments and research methods, which are described in detail, e.g., in works **[L. 3–7]**.

It is worth emphasising at this point that there are standards that specify the methods and conditions for conducting laboratory studies. Despite the given requirements, it is important to analyse whether they will allow to achieve the intended research purpose each time. An example may be the ASTM F2033 standard **[L. 8]**, where the control of the manufactured (before operation process) elements of the head-acetabulum friction node of the artificial hip joint according to this standard should use the contact method of surface topography studies. The manufacturing quality should be evaluated, among others, based on the surface roughness described by the Ra parameter (2D roughness profile parameter). Additionally, (small print located at the end of document) it is suggested to use other parameters in the analysis, including 3D surface parameters, as well as used in scanning electron microscope studies. Unfortunately, friction node elements, assessed during or after the operation process, should not be tested using contact methods. It is similar in the case of soft materials (e.g. polymers); the use of contact methods in testing can affect the modification of the manufactured surface, which could result in its different behaviour during the operation process. Therefore, in such cases, it is worth considering the use of non-contact methods in the research of surface topography manufactured and operated so that their comparative analysis is possible **[L. 7]**.

The tribological wear mechanism (oxidative, hydrogen, abrasive, adhesive, deformation, scuffing, fatigue, thermal, and fretting **[L. 9, 10]**) can be determined on the surface characteristics, e.g., image analysis (surface morphology). Many works have been published in the literature where the assessment of the operated surface topography and wear traces is mainly made on the basis of surface images from optical microscope OM **[L. 11**, **12]**, scanning electron microscope SEM **[L. 13**, **14]**, and atomic force microscope AFM **[L. 15**, **16]**; appropriate software also enables the dimensioning of characteristic features, including wear traces (mainly the width of the wear trace).

The operated surface topography can be characterised in two ways, depending on the type of contact between the surfaces of friction elements. Assuming two types of surface contact: concentrated contact (no 1:1 contact of the co-operating surfaces of the friction node elements, resulting in a wear trace, the shape of which depends on the contact geometry of the friction elements) and distributed contact (1:1 contact of the co-operating surfaces of the friction node or complete surface contact of one element with part of the surface of the other element; no marked wear trace on the surface of the first element, but visible wear products on the surface of the second element in the form of the transferred material from the first element), it is possible to analyse the wear trace (dimensions – width and depth) and the operated surface topography, respectively. The analysis can be carried out as a 2D analysis (analysis of the profile and characteristics of the wear traces/particles) and as a 3D analysis (analysis of the surface topography and wear traces/particles). In addition, in the case of concentrated contact, it is possible to characterise the surface topography inside the wear trace. Unfortunately, in the literature, there is rarely a comprehensive approach to characterising a surface modified in the operation process. In most cases, the authors limited only to selected elements of non–parametric–qualitative analysis (surface morphology analysis) and parametric–quantitative analysis (dimensions of the wear trace – width based on images and width and depth based on the profile as part of the 2D analysis; surface topography – functions and parameters of the surface texture as part of the 3D analysis).

In this work, which is a continuation of the issue of the tribological systems research methodology described in work **[L. 1]**, a general concept of the operating surface research methodology is presented, paying attention to the use of measuring instruments for studying surface topography. It was shown how the use of an appropriate research methodology could help characterise the wear mechanism, wear traces and the operated surface topography of the friction elements of the tribological system while constituting a comprehensive approach to assessing these surfaces.

CONCEPT FOR THE RESEARCH METHODOLOGY

The issues raised in this work concern the concept of a machined surface topography research methodology modified in the operation process. The modification of the surface topography formed in the technological process occurs as a result of various factors, including the materials properties of the friction elements, the geometry of friction elements (from macro to micro and even nano scale) and the environmental conditions in which the operation process takes place **[L. 7, 9, 10]**.

The result of the operation (friction) process, apart from the values measured in laboratory conditions (e.g., friction force, friction coefficient/friction moment), is tribological wear. Wear is measured in absolute or relative terms. The absolute measure of wear can be the mass (mass wear), the volume (volume wear) of the removed material or the thickness (linear wear) of the removed material/deformed surface layer. A relative measure of wear is the wear intensity (wear rate) defined as a reference to mass, volume or linear loss to a unit of time, friction distance or friction work **[L. 8]**. In addition, wear is characterised by identifying the wear mechanism and products, the operating surface's shape and wear traces.

The research methodology of surface topography modified in the operation process requires defining the research purpose, to achieve which an appropriate research programme is adopted along with research methods and tools (research and measuring instruments), as well as the presenting method of the results with their analysis and inference.

The concept for a research methodology of the operated surface topography of friction node elements, taking into account the type of surface contact of the co-acting elements, is presented in **Figure 1**.

Due to the need to obtain complementary information on the wear mechanism, wear traces and surface topography, the studies of the surface modified in the operation process should take into account the use of devices, e.g. optical microscope OM, scanning electron microscope SEM (including the EDS microanalyser), atomic force microscope AFM and other stereometrics research methods SRM (surface/stereometrics research methods – contact and non-contact research methods) such as contact profilometer, confocal microscope or interference microscope, etc.

On the basis of non-parametric (qualitative) analysis and parametric (quantitative) analysis – both the 2D (profile analysis) and the 3D (topography analysis) – it will be possible to characterise the studied surfaces comprehensively.

The concept of a research methodology is discussed in the studies examples conducted or co-conducted by the author of this work. The presented results concern various metallic materials, including titanium alloy and tool steel, and aim to show what information can be obtained using the adopted research and analysis methodology for any tribological system. Therefore, it is possible to implement this research methodology of operated surface topography for various materials used for friction node elements in tribological systems.

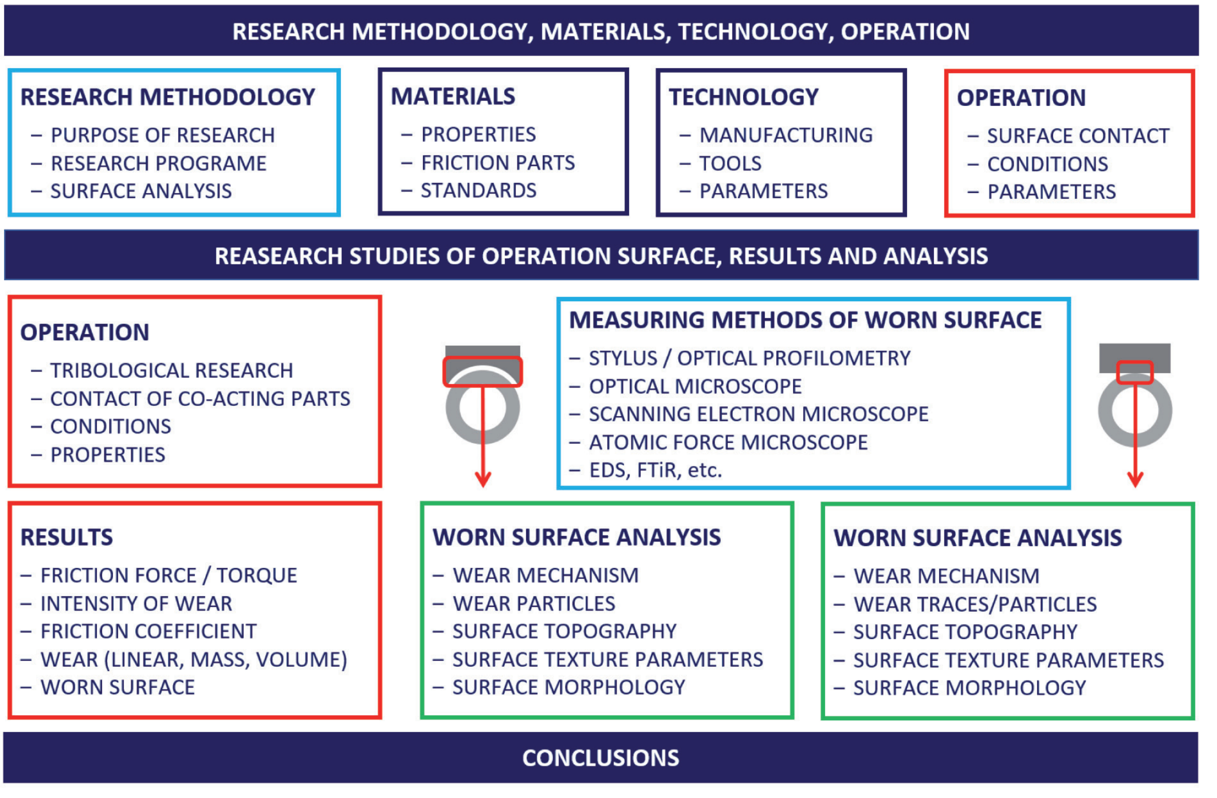


Fig. 1. Research concept of the surface topography modified in the operation process
Rys. 1. Koncepcja badań topografii powierzchni modyfikowanej w procesie eksploatacji

DESCRIPTION AND RESEARCH EXAMPLES

Bearing in mind that there are various friction nodes in the tribological systems of technical objects and the related type of surface contact of co-acting elements, a different approach to research and analysis of the operated surface topography should be considered.

The presented concept for a research methodology of surface topography takes into account the research and analysis of tribological wear traces. In this work, the various approaches to the studies depending on the type of contact between the surfaces of the friction elements of the tribological system are shown. The selected research results best illustrate these approaches carried out to date, presented in the tables below.

The purpose of the research conducted in the field of surface topography modified in the operation process is, first of all, to identify the wear mechanism and wear particles, as well as the quantitative (parametric) and qualitative (non-parametric) characteristics of the operated/worn surfaces, including wear traces (transferred material – area, volume, height and width). This scope of research and analysis concerns the case of distributed contact. **Table 1** shows the results of the 2D/3D studies and analyses, where the distributed contact of co-acting surfaces is considered – results of the own works, including **[L. 18]**.

In the case of concentrated contact, the purpose of the research in the field of surface topography modified in the operation process, apart from identifying the wear mechanism, is the 2D and 3D analysis of wear traces observed on the surfaces of the friction node elements of the tribological system. The 2D analysis is carried out based on the profile, where the width and depth of the wear trace are determined. The 3D analysis takes into account the dimensions, area and volume of the wear trace. In addition, a 3D analysis of the worn surface inside the wear trace is performed in the case of concentrated contact. The 2D and 3D analysis of the operating surface of the co-acting element (without the marked wear trace) is also carried out. In both cases, the characteristics of the operated surface topography are carried out similarly to the case of distributed contact. **Table 2** presents the results of the studies and 3D analysis of the surface

Table 1. Results of the operated surface topography (distributed contact)
Tabela 1. Wyniki badań topografii powierzchni eksploatowanej (kontakt rozłożony)

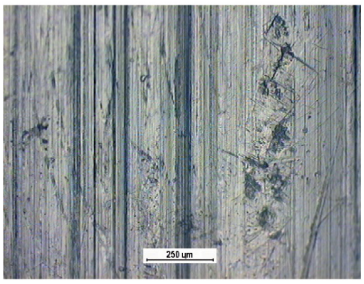
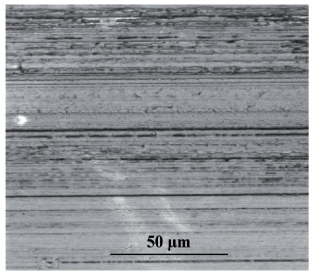
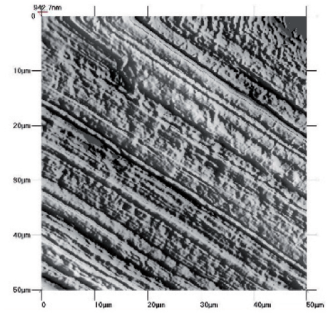
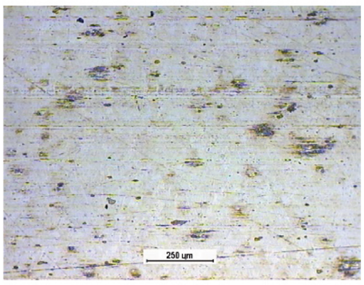
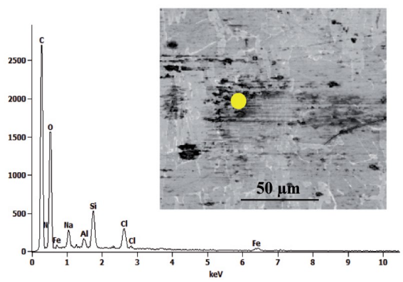
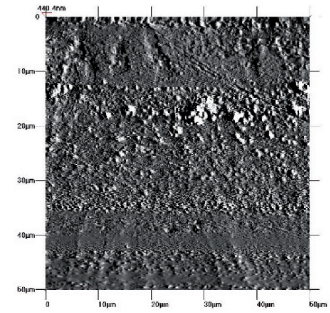
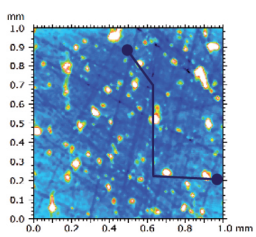
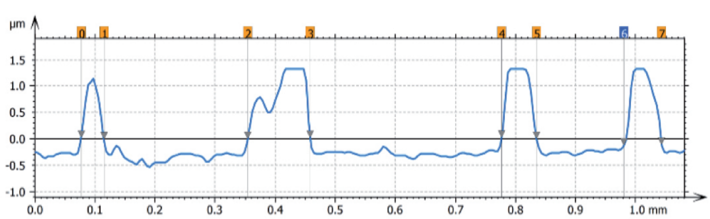
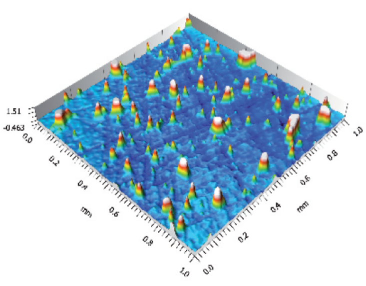
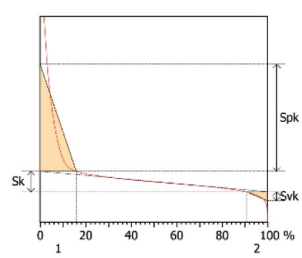
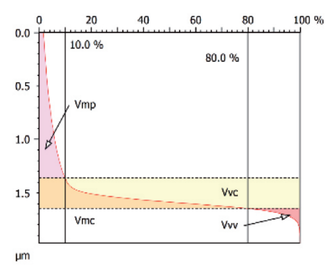
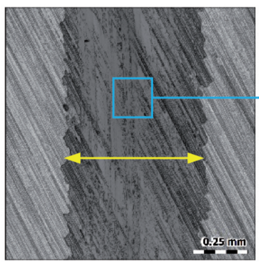
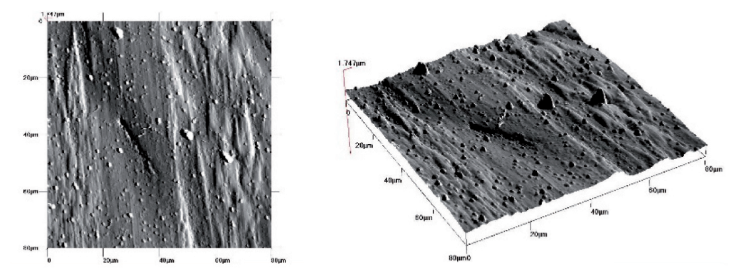
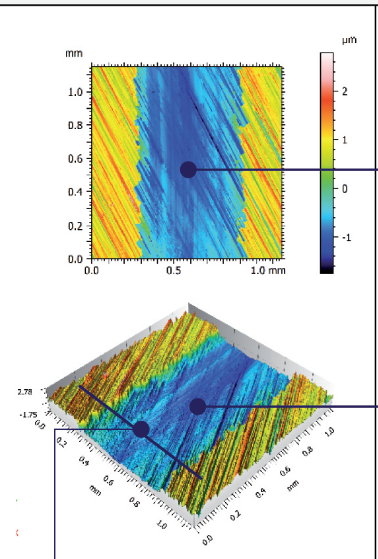
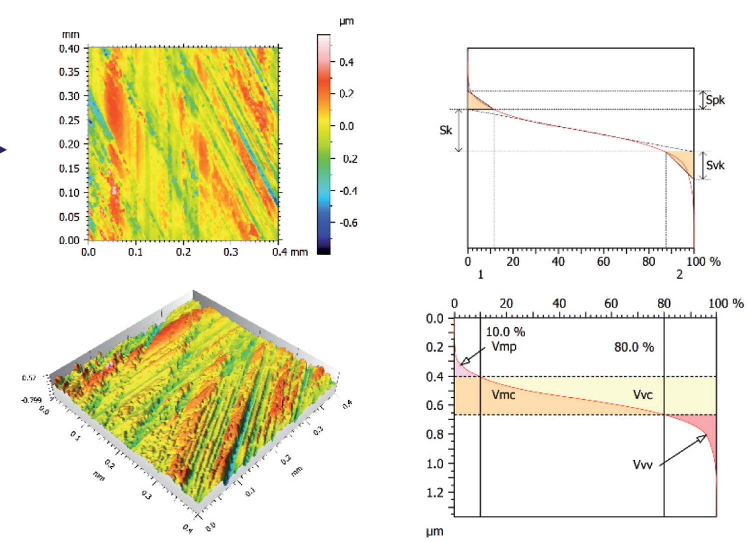
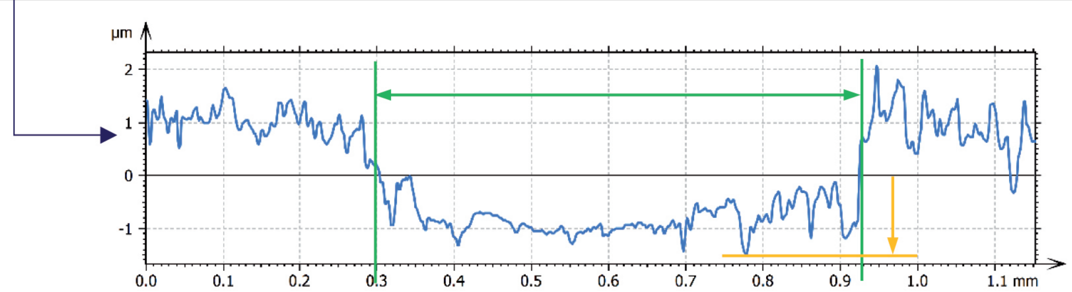
OM	SEM/EDS	AFM
		
		
SRM – 3D and 2D analysis (surface with transferred material)		
		
		
SRM – parametric analysis		
ISO 25178: Sa, Sq, Sz, Sp, Sv, Ssk, Sku, Sal, Str, Std, Sdq, Sdr, Spd, etc.		
ISO 4287: Ra, Rq, Rz, Rp, Rv, Rsk, Rku, etc.		
Scope of analysis and inference		
Non-parametric description (based on graphs, photos and surface maps) and parametric description (based on 2D and 3D parameters) of the co-acting surfaces of friction node elements created during the operation process. Determination of the wear degree of the friction node elements of a given tribological system. Identification of the wear mechanism and wear particles (qualitative and quantitative analysis).		

Table 2. Results of the operated surface topography (concentrated contact) – wear trace
Tabela 2. Wyniki badań topografii powierzchni eksploatowanej (kontakt skoncentrowany) – ślad zużycia

OM	AFM
 	
SRM – 3D analysis	
	
SRM – 2D analysis	
 	
SRM – parametric analysis	
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.	
Scope of analysis and inference	
Non-parametric description (based on graphs, photos and surface maps) and parametric description (based on 2D and 3D parameters) of the co-acting surfaces of friction node elements as well as the wear trace and surface inside wear trace, created during the operation process. Characteristics of the wear trace with identification the wear degree and the wear mechanism of friction surfaces (qualitative and quantitative analysis).	

topography as well as the 2D analysis of the wear trace for concentrated contact – results of the own works, including **[L. 19]**.

In all considered cases, the selection of materials for the friction node elements of the tribological system, the manufacturing technology of these elements and the research equipment for the implementation of the tribological (friction-wear) test programme are the components of the result of the operation process. This result is evaluated on the basis of the conducted research and analysis of the topography of the exploited surface and has an impact on future actions regarding tribological systems of technical objects.

CONCLUSIONS

The presented concept for a research methodology is intended to encourage researchers to conduct complementary research on the surface topography formed in the operation process using various measuring instruments.

Exemplary results of studies presented in this work show what kind of information is provided by the use of various research methods and measuring instruments, what conclusions can be drawn on the basis of the collected information, and how they should be used in future studies of tribological systems.

An important issue that has been highlighted is the definition of the research purpose at the beginning because the research purpose entails consequences in the form of a research programme and the selection of research and measuring methods, as well as the method of analysing the obtained results. The determination of the research methodology is related to the type of tribological system and the materials from which its elements were made. The type of material and the surface contact of the friction elements of the tribological system determine the selection of research and measuring instruments, as well as the approach to analysis and inference.

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