

Tribological researches of triboelements topography of hob milling process of cylindrical gear serration

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Abstract. Hob milling process is one of the most important links in the chain of machining because productivity, final geometrical accuracy and gear cutting are very dependent on it. The quality of the machining of gear serration is one of the conditions for achieving the required quality of the work-piece. In this paper the methodology for the identification of topography of tool teeth and gear serration produced by uncoated and coated model and real hob milling tool is presented.

1 Introduction

It is well known that the structure and individual components of modern industrial complexes represent superior range and the most complex products in the respective fields of science. Consequently, the greatest technological achievements of various industrial branches are merged at the constructors of modern industrial complexes and they are integrated into their products. The world market today is being tackled with rapid and continuous changes. Generalised information about a production environment in the 21st century is given in Fig. 1 [1-3] where can be seen also a number of factors affecting the world market.



Fig. 1. Manufacturing environment in 21st century.

Furthermore, the rapid development of industrial production in the world has caused the need for extensive research in all fields, even in the field of machining. Due to the previous data, a significant contribution was made to the development of new types of work-piece materials, tool materials, machines, cutting tools, deforming tools, fixtures, measuring devices, cutting fluids and a better understanding of the nature of the cutting process in different machining conditions [4]. The development of technology of hob milling is successfully used in roughing as well as fine machining of serration. For that reason, the demand for process optimization has been grown up, both from the

point of view of the machined surface quality and from the point of view of productivity. A prerequisite for the successful optimization and adequate process control is its identification, respectively identification of occurrences originated during hob milling. Surfaces produced by metal cutting processes have the traces of cutting elements passage. The thin layer beneath the working surface has the deformed crystal structure. Also, the hardness of this layer is sometimes even higher than the hardness of the basic material [5].

In this paper an overview of the research of the triboelements topography of the tribomechanical system in the gear cutting is presented. The research is realized mainly at the Faculty of Technical Sciences, University of Novi Sad and it is also based on cooperation between academic partners from Eastern and Central Europe.

2 Production process and product

In the production process, a man adjusts things from the nature to his own needs using work tools by changing their form, physical and chemical composition. In contemporary conditions, the development of products as a necessary prerequisite for competitiveness in the market presents by its characteristics: quality-price-term (Fig. 2) [6, 7].

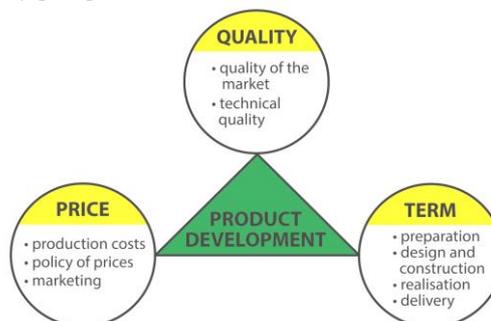


Fig. 2. Characteristics of product development.

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Quality as one of the key features in product development includes both market quality and technical quality. Observing the development of products as the development of machine and other technical systems, it is evident that market rules pose sharper and more complex requirements. The quality of the product is influenced by a large number of factors conditionally classified in three large groups (Fig. 3) [6, 7], so the quality of the product can be considered as a function of quality of construction, quality of production and quality of exploitation.

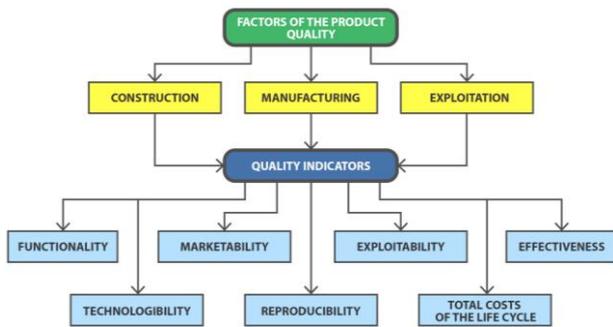


Fig. 3. Influencing factors on product quality.

Today, in the evaluation and assessment of the quality of the product, different complex parameters are used, the most recognizable of which are shown in Fig. 2 [6]. It is important to note that each of them is a complex size, depending on several factors, stochastic or deterministic character.

3 Gear cutting and the topography of the surface

Gear cutting can be done by various methods and procedures. Hob milling, as one of the most complex machining processes, has the widest application in the process of gear cutting of cylindrical gears due to the high productivity of the process. The complicated kinematic and geometric relationships between the hob milling tool and the work-piece create a series of difficulties and problems that prevent the optimal use of tool and machine (Fig. 4 [8, 2]).

Hob milling is a multi-parametric and complex method for the gear cutting of cylindrical gears. It is an efficient machining process for the production of serration of high quality cylindrical gears. This process is also associated with the complicated formation and flow of chips, as well as with the hard-to-describe wear mechanisms of hob milling [4], [8-14]. A comprehensive knowledge of the gear cutting process is crucial for solving the demands of the global market. The mentioned development is constantly involved in the development and production of machine tools for gear cutting.

Manufacturers of involute cylindrical gears during the process of their production, regardless of their size, from a few millimetres to several meters are faced with common technological problems. The predictability of machining parameters, such as geometry and chip flow, wear of the hob milling tool, etc., with regard to work-

piece, tool and production data, is of great interest for research and industry. Production operations and methods of gear cutting in mass production depend on various parameters such as the cost of gear cutting, production philosophy, practical experience, etc. A common strategy is to achieve the highest possible accuracy during rough machining of gear serration and to carry out thermal treatment with the necessary tolerance to completely avoid finishing of the gear serration [4, 7, 14, 15].

The process of the gear cutting by hob milling is characterized by different thicknesses and lengths of the chips, and the materials from which the cutting edge of hob milling tools are made should have significant tenacity and hardness. Based on the previous, significant attention is paid to the strengthening of the hob milling tool by applying a permanent layer to the working surfaces of the hob milling tool. The application of coated hob milling tools is conditioned by their high efficiency. Thanks to the application of the coating layer, the strength is increased by 1.5-3 times. Until now there is no correlation between the strength of the hob milling tool and the properties of the coating layer, and the issues of optimizing the properties of the complex layer and the tool base remain open. There are also difficulties in the industrial application of progressive surface reinforcement technology and the rational application of a reinforced hob milling tool.

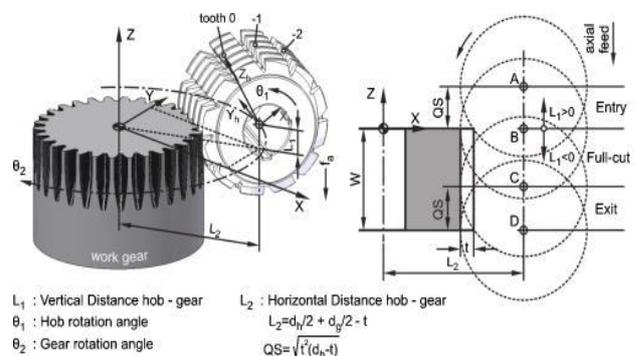
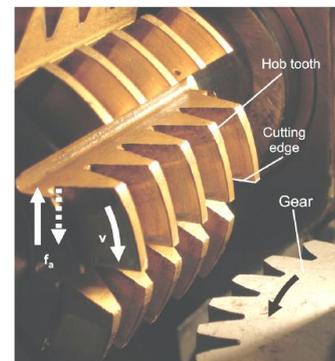


Fig. 4. Hob milling kinematics.

The tendency of the material development for the hob milling tools and the technology of their surface reinforcement are conditioned by the need directed towards improving the physical and mechanical properties of the material for the hob milling tools, among which strength, thermostability, resistance and

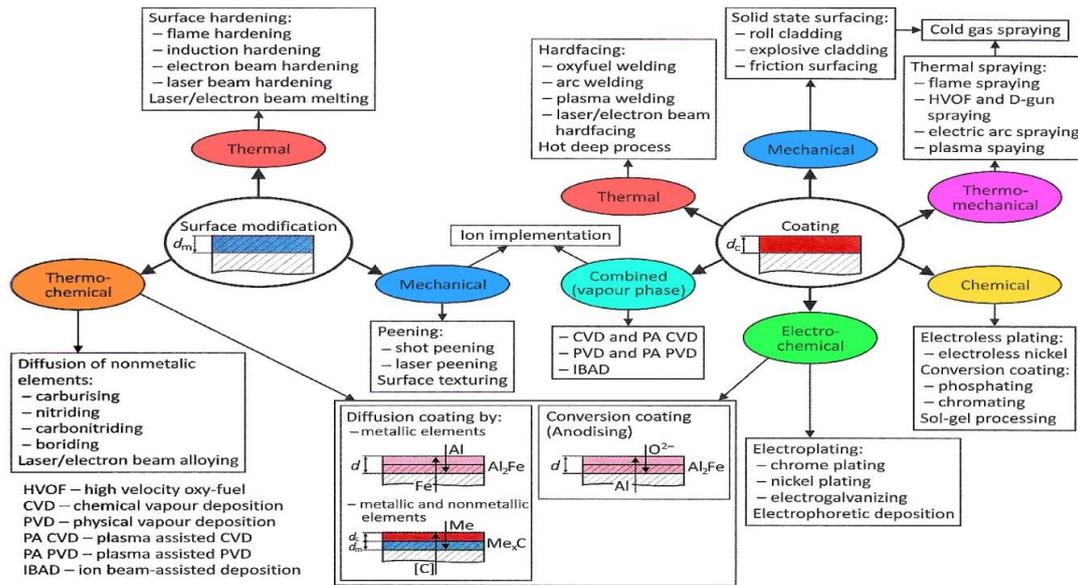


Fig. 5. Overview of main surface engineering (surface modification and coating deposition) techniques.

brittleness have been considered to be important, while other properties are considered to be less important. Ignoring the importance of certain properties of the hob milling tool materials is one of the main reasons for the lack of understanding of the main functions of the layer's stability on the hob milling tool. There are more than one hundred different methods of surface coating of metals and alloys, by which it is possible to increase the efficiency of the tool to a certain extent [16-22]. An overview of basic techniques and surface engineering (surface modification and application of a layer) is shown in Fig. 5 [16, 17, 22].

In Fig. 6 [17, 22], coating techniques based on the physical state of the applied material are given. The surface coating technique is perfected by a rapid rhythm, which greatly contributes to the development of theoretical concepts in the field of surface resistance of materials. Today, high-speed steel hob milling tools continue to be used primarily for gear cutting in the automotive industry, especially in the production of truck changers. The further evolution of metallurgy of powdered high-speed steel in combination with the application of PVD layers has contributed to this application and the development of high-speed steel. Coated hob milling tools made of high-speed steels are also used for dry gear cutting of cylindrical gears [8-11].

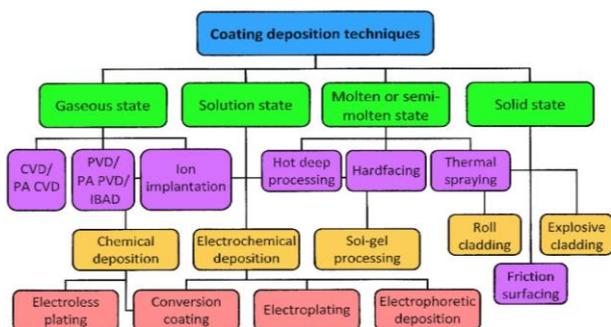


Fig. 6. Classification of the main coating deposition techniques

Most of the hob milling tools can be classified into three groups according to their design (Fig. 7a [2-4, 7-9]). Integrated hob milling tools can be manufactured from conventional high-speed steel, high-speed steels produced by sintering and for smaller modules made of cemented-carbide. All of the aforementioned hob milling tools can be coated. The hob milling tools with changeable teeth or strips from high speed steel, cemented-carbide or sintered alloy consist of a basic body made of cheaper material and are particularly suitable for larger diameters and larger modules. The hob milling tools with changeable teeth beside that they allow larger constructive back angles, they also have a relatively large, usable cutting length (see Fig. 7a [2-4, 7-9]).

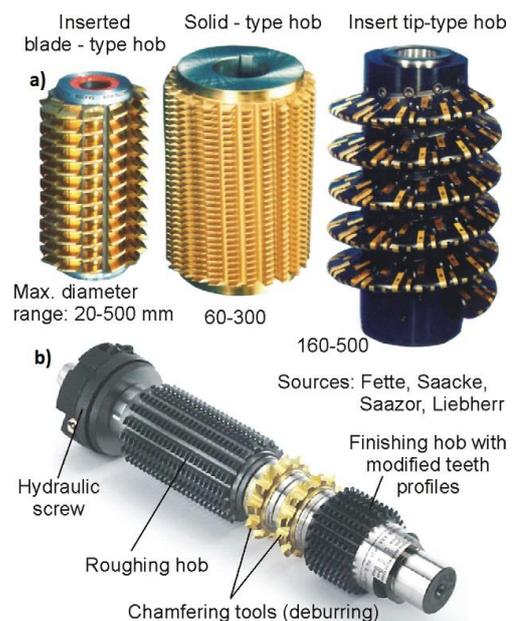


Fig. 7. Modern hob milling tools.

Various variants of hob milling tools that combine different processes such as roughing and finishing and machining of chamfers for removing irregularities (Fig. 7b [2-4, 7-9]) have also been developed. In order to increase the productivity of the hob milling, gear cutting process is very close to the limit of the technological capabilities of the machine tools and the hob milling machines. Therefore, the optimal choice of the hob milling tool material is important in achieving this goal.

Characteristic parameters formed during the technological process define macrogeometry and microgeometry of contact surfaces. The connection between topography of contact surfaces and the development of tribological processes is very complex. The change of topography in the development of tribological processes can be shown by the model as in the Fig. 8 [10, 23].

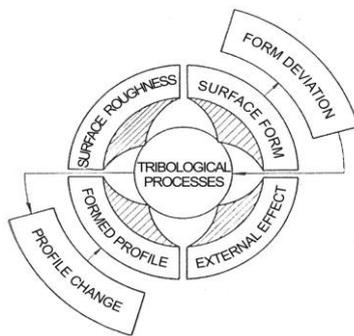


Fig. 8. Change of topography during development of tribological processes.

For the correct analysis of tribological processes, but also tribologically correct construction, the roughness of the contact surfaces is especially significant. Macrogeometry can be repaired during the technological process itself by working properly on the system; machine-fittings-tool-work-piece. Roughness has a stochastic element and it is a consequence of random processes. It cannot be avoided, but it can be managed to a large extent in the technological process of machining [24].

It is known that for analysis of the roughness of the machined surface of the elements, there are more than 30 parameters that are less and those that are more represented. The basic parameters of roughness are defined according to national and international standards. The first three parameters R_a , R_{max} and R_z represent a small group of the three most common parameters, while R_t , R_q and R_p are the parameters that are also used, but considerably less than the three previously mentioned roughness parameters. Roughness significantly affects the actual surface of the contact, that is, the surface on which the contact of the micronuclei that forms the topography is realized. The actual surface of the contact depends on the micro and macro geometric characteristics of the surfaces in contact, from the corrugation, form errors, physical mechanical properties of the surface layer, from the load, etc. With the load parameter, the actual surface of the contact

increases, and the growth is conditioned by the emergence of new contact points [25].

In constructing of tribo-mechanical elements in addition to the types of materials, it is necessary to define the shape of the element, its dimensions, tolerances, thermo-chemical treatment and the quality of surface machining of each surface. The geometric shape of each surface is commonly referred to as surface texture. Conventional when the surface texture is measured quantitatively, only roughness is measured and the waviness and shape elements are mechanically, electrically or digitally filtered from the obtained data.

The quality of machining affects the exploitative characteristics of the elements and their price, which is why it is necessary to pay great attention to the choice of machining quality. The constructor should not prescribe very precise machining of the surfaces of the elements so that they would be smoother because it is expensive and the production would be very uneconomic. Therefore, it is necessary to find the optimum functionality and economy. The surface has to be as rough as possible to make the machining of this surface cheaper, but it has to be obligatory to fulfil the functionality requirement [26].

The nature of the materials of the machine elements, the loads in the contact zone, the relative velocities, the topography of the contact surfaces, and the temperature in the contact zone influence on the tribological characteristics of the elements, and hence on the characteristics of the tribo-mechanical systems. The surfaces of the tribo-mechanical elements of the machines through which mutual contact is realized are essentially thin layers of materials whose composition and properties differ significantly from the properties of the basic mass element material. There are a significant number of tribo-mechanical systems in the energy sector. Gear cutting is the most important operation in the production of gears. The quality of the gear cutting is one of the conditions for achieving the required quality of the work-piece. The gear is an element of a large number of tribo-mechanical systems. The geometrical parameters of the hob milling, the accuracy of the profiling and the accuracy of manufacture significantly affect the productivity and machining costs [2, 3, 7, 22, 23, 27]. In this paper, wear and roughness of the real hob milling tool, the topography and roughness parameters of lateral flank and tooth-face of the model hob milling tools are analyzed before and after gear cutting of cylindrical gears.

4 Experimental results of triboelements topography of hob milling process of cylindrical gear serration

Starting from the analysis of the basic legalities of the gear cutting of cylindrical gears by hob milling, the research took place in two basic directions:

- investigation of the influence of geometric parameters and constructions of the hob milling tools on tribological processes;
- investigation of the influence of the parameters of the cutting regime on tribological processes.

According to the research plan of the full study of modelling and optimization of hob milling process, the analysis of the topography of gear cutting tools and machined teeth of spur wheels are also included. Within current paper, only parts of the results related to the topography of triboelements for gear cutting are given. Based on the experiment plan, the research was carried out on uncoated and coated model hob milling tools with modules $m = 3 \text{ mm}$ and $m = 5 \text{ mm}$.

4.1 Research of triboelements topography of hob milling process in real conditions of gear cutting of cylindrical gears

In the cutting process the contact between the hob milling tool and the work-piece material is accomplished between the scraping and the tooth-face and between the tooth clearance surface and the machined surface. Tribological processing occurring in the cutting process on both tooth surface of the tool develops under specific conditions. The influence of the hob milling tool wear on the characteristics of state and output effects of the machining process is extremely great and negative.

The objective of this part of the research is to determine the correlation between the roughness and degree of wear of the hob milling tool elements. In order to accomplish this, it was necessary to perform topography of single-tooth hob milling tool. The topography of the analysed tools was recorded by Talysurf-Taylor Hobson instrument. Before conducting the experiment, the topography of new coated and uncoated teeth of the hob milling tool has been recorded. Recording of the topography of all tools has been performed on input lateral flank, output lateral flank and tooth-face. The topography has been recorded on the left and right tooth flank along the involute as well as along the tooth itself.

On the basis of experimental results graphic correlation between the roughness and wear degree of cutting element of model hob milling tool can be obtained [5, 10]. Roughness profiles of machined surface, obtained as a record on the apparatus for roughness measuring represent an incidental occurrence. In production conditions development of the wear process and corresponding roughness has been followed. In Fig. 9 development of wear process on the output lateral flank of the coated hob milling tool 05 (a) and its roughness R_a (b), wear on the output lateral flank of the uncoated hob milling tool 58 (c) and its roughness R_a (d) are given.

Based on the data from Fig. 9 between roughness and wear degree of hob milling tool, a cutting element correlation has been determined – equations (1), (2), (3), (4). The correlation between roughness and degree of wear of the cutting element of uncoated hob milling tool has the form:

$$h = 0.07314 \cdot R_a^{5.041872} \quad (1)$$

$$R_a = 1.67992 \cdot h^{0.19834} \quad (2)$$

where the coefficient of correlation $r = 0.9901$.

The correlation between roughness and degree of wear of the cutting element of coated hob milling tool has the form:

$$h = 0.28929 \cdot R_a^{7.55980} \quad (3)$$

$$R_a = 1.17830 \cdot h^{0.13828} \quad (4)$$

where the coefficient of correlation $r = 0.96$.

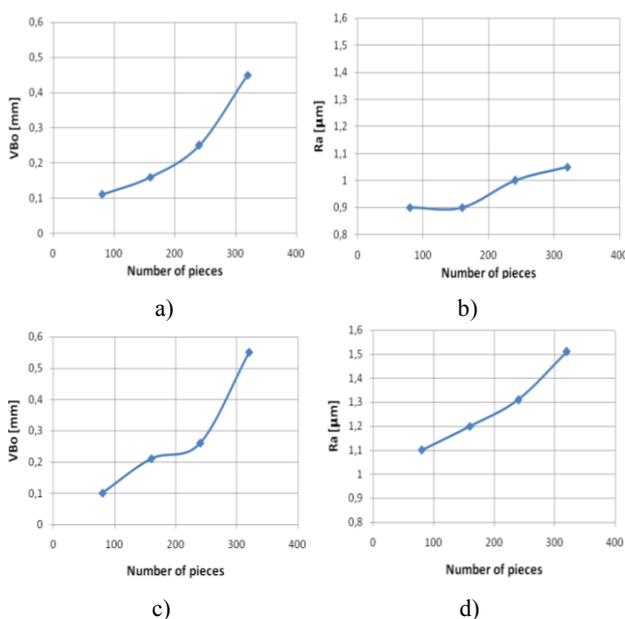


Fig. 9. Development of wear process on the output lateral flank of tool 05 (a) and its roughness (b), and wear process on the output lateral flank of tool 58 (c) and its roughness (d).

Obtained dependency of roughness parameters of gear teeth of machined surface on the wear parameters of hob milling tool has high correlation coefficients in particular case. Based on this, it is possible to follow indirectly for that case the hob milling tool wear also by following the roughness.

4.2 Research of triboelements topography of hob milling process in laboratory conditions of gear cutting of cylindrical gears

In the research of the process of hob milling of cylindrical gears serration it is necessary to perform long-term experimental tests which require resources and efforts and it is extremely difficult to implement them in the real production process. In that relation a method was developed, and devices for model testing of the process of hob milling, [14]. In Fig. 10 an integral hob milling tool, a device for model hob milling and a single-tooth tool detail are given.



Fig. 10. Integral and model tools with a single-tooth tool detail.

4.2.1 Roughness parameters of lateral flank of model hob milling tools during gear cutting of cylindrical gears

At the beginning of experimental topography research 392 model hob milling tools were identified based on certain characteristics. The roughness parameters were first measured on unworn tools, and then on the same tools after reaching the wear criterion. Roughness parameters are measured on model tools, which were already worn before this research. From the group of 392 tools 104 model hob milling tools have been allocated with modules $m = 3$ mm and $m = 5$ mm (Table 1).

Table 1. Subtypes of model hob milling tools $m = 3$ mm and $m = 5$ mm .

MODULE		1	2	3	4
$m = 3$ mm	$m = 5$ mm				
UNCOATED		*	*		
COATED				*	*
UNWORN		*		*	
WORN-OUT			*		*

In each subtype, there are 13 model hob milling tools, and in Fig. 11 a subtype of uncoated worn-out model hob milling tools with the module $m = 5$ mm is given.



Fig. 11. Uncoated worn-out model hob milling tools with the module $m = 5$ mm .

In these experiments, a model hob milling tools made of HS 6-5-25 was used and a number of tools were coated with TiN. To measure roughness parameters, a MahrSurf PS1 device was connected to a computer, so the measurement results were obtained in electronic form (Fig. 12 [27, 23]).



Fig. 12. MahrSurf device connected to computer.

The surfaces of model hob milling tools and measuring directions are shown in Fig. 13 [7, 27, 23].

In this part of the paper, two types of experimental research were performed. The first experimental study presents a comparative analysis of the roughness parameters of the input and output lateral back surfaces of the model hob milling tools that were measured in the unworn and worn-out state.

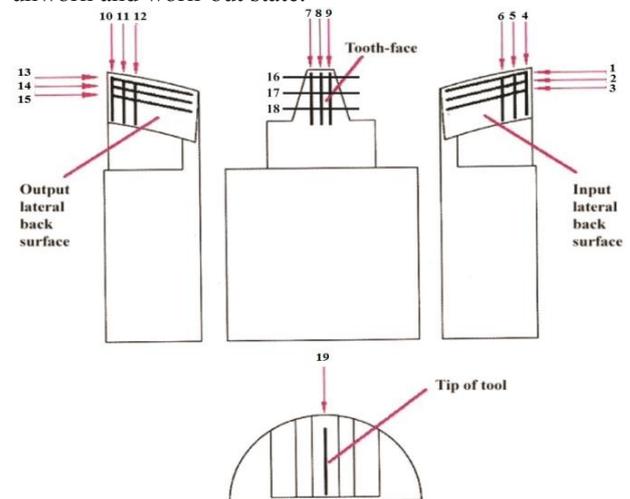


Fig. 13. Tool surfaces and directions of measuring.

The second experimental study contains the analysis of the roughness parameters of the input and output side lateral flank of four subgroups of thirteen model hob milling tools. The results of the research are shown in diagrams and a part of the results is given in Figs. 14-23.

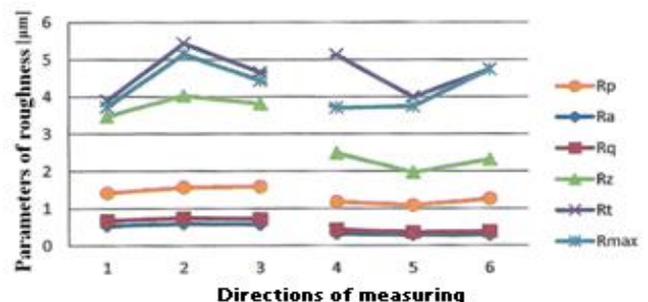


Fig. 14. Diagram of roughness parameters of the input lateral flank of uncoated tool 7 unworn module $m = 3$ mm .

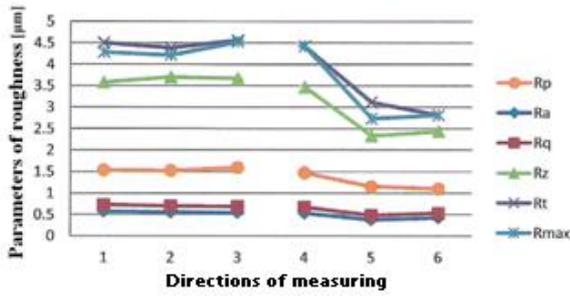


Fig. 15. Diagram of roughness parameters of the input lateral flank of unworn tool 7 worn-out module $m = 3$ mm .

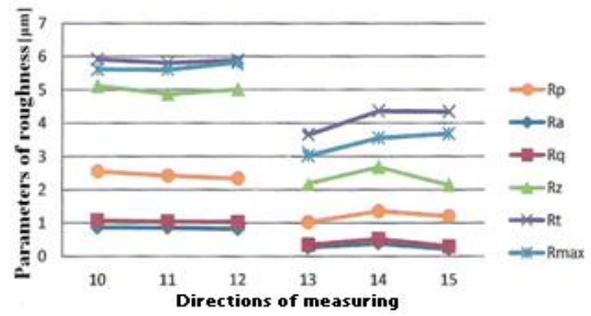


Fig. 19. Diagram of roughness parameters of the output lateral flank of unworn tool 22 worn-out module $m = 3$ mm .

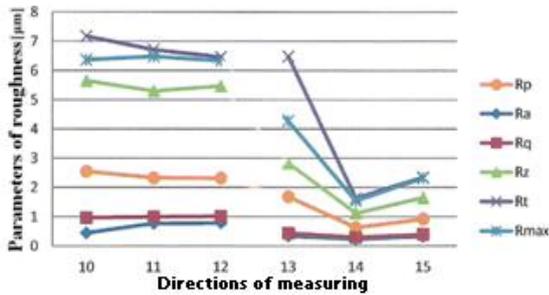


Fig. 16. Diagram of roughness parameters of the output lateral flank of unworn tool 7 worn-out module $m = 3$ mm .

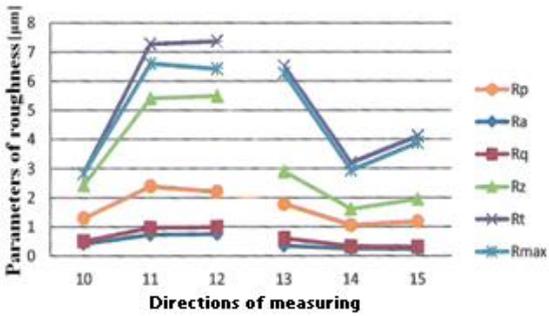


Fig. 17. Diagram of roughness parameters of the output lateral flank of unworn tool 7 worn-out module $m = 3$ mm .

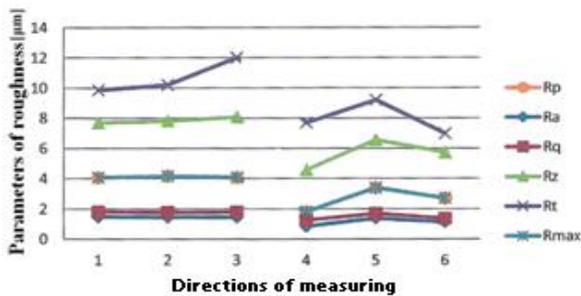


Fig. 18. Diagram of roughness parameters of the input lateral flank of unworn tool 22 worn-out module $m = 3$ mm .

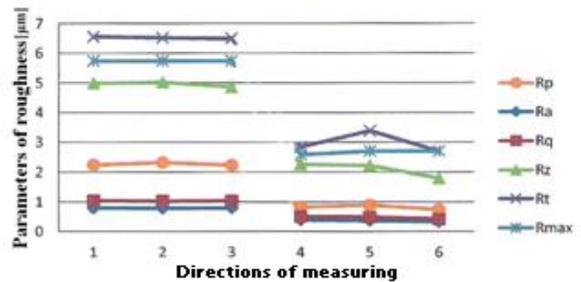


Fig. 20. Diagram of roughness parameters of the input lateral flank of unworn tool 55 worn-out module $m = 5$ mm .

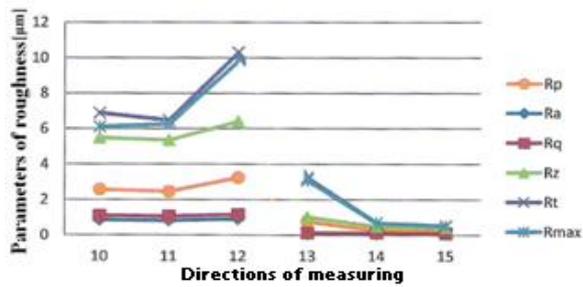


Fig. 21. Diagram of roughness parameters of the output lateral flank of uncoated tool 55 worn-out module $m = 5$ mm .

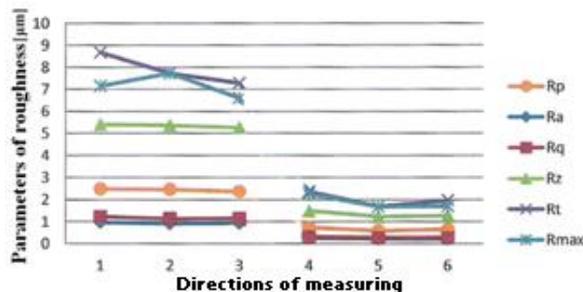


Fig. 22. Diagram of roughness parameters of the input lateral flank of coated tool 73 worn-out module $m = 5$ mm .

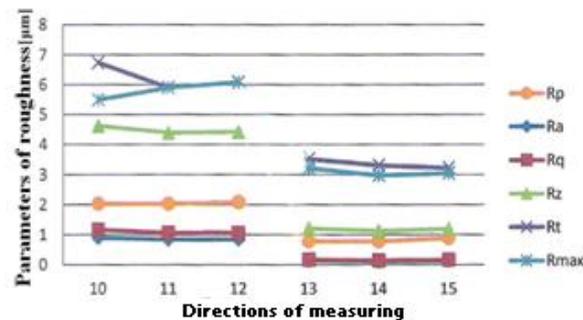


Fig. 23. Diagram of roughness parameters of the output lateral flank of coated tool 73 worn-out module $m = 5$ mm .

As it was already mentioned, the second part of the experiment included analyses of the roughness parameters of four groups of thirteen worn-out model hob milling tools. For the input lateral flank of all of them it can be concluded that the maximum values of the roughness parameters most often occur on the first three directions of measurement, because the tool of the module $m = 5$ mm has wider flank wear and minimum in the fifth and sixth direction of measurement in the groups in which the coated model tools were analyzed, while in the groups where the uncoated model tools were analyzed maximum roughness values were moved to the first and third direction of measurement, and the minimum values remained on the same measurement directions as coated, also with the remark that the results of each parameter vary widely.

From the same experimental part but related to the analyses of the roughness parameters of the output lateral flank of the above mentioned subgroups of hob milling tools, it can be concluded that the maximum

values of the roughness parameters are most commonly occurring on the longitudinal tenth direction of measurement, while in the case of uncoated tools maximum values of the roughness parameters displaced in the longitudinal eleventh and twelfth directions of measurement, which can be explained by the fact that the flank wear on the output lateral flank are higher in the case of uncoated tools in the transversal fourteenth and fifteenth direction of measurement. Moreover, the results of each parameter vary in wide ranges.

Based on these two parts of the experimental research it can be concluded that all the maximum values of roughness parameters at characteristic surfaces of the model hob milling tools are represented in longitudinal direction of measurement, while all minimum value of roughness parameters are represented in the cross-direction of measurement. Explanation arises from the fact that the measuring needle used for measurements in the directions of 1, 2 and 3, respectively and 10, 11 and 12 was moving in the direction of the normal to the grooves resulting from the final machining of the characteristic surface of model hob milling tools. The movement of the measuring needle was parallel with the aforementioned grooves for the directions 4, 5 and 6, respectively and 13, 14 and 15.

4.2.2 Roughness parameters of the tooth-face of model hob milling tools

Within this part of the paper only parts of the results relating to the topography of tools for gear cutting are given. According to the plan of the experiment, researches were carried out for uncoated and coated model hob milling tools with modules $m = 3$ mm and $m = 5$ mm . At the beginning of experimental researches of topography, 392 model hob milling tools were identified based on certain characteristics. Roughness parameters are measured initially for unworn tools, and then for the model tools that were already worn before these researches of topography. From the group of 392 tools, 56 model hob milling tools with the module $m = 3$ mm and $m = 5$ mm (Tab. 1) were separated. In each subtype there are 7 model hob milling tools (Fig. 24 and Fig. 25), and in Fig. 26 representatives of the model hob milling tools with the module $m = 3$ mm and $m = 5$ mm are given.



Fig. 24. Model hob milling tools $m = 3$ mm .



Fig. 25. Model hob milling tools $m = 5$ mm .

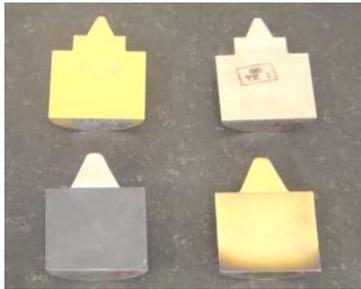


Fig. 26. Representatives of the model hob milling tools.

In these experiments, a model hob milling tools made of HS 6-5-25 were used and some of them were coated with TiN. To measure the roughness parameters, the Mitutoyo SJ-301 device was connected to the computer (Fig. 27 [7]), so the measurement results were obtained electronically.



Fig. 27. Measurement results in the software.

The software interface of Mitutoyo SJ-301 device is shown in Fig. 27 [7]. The Figure shows the communication conditions that are important for connecting device and computer. They define which input (COM1) connects the computer and the Mitutoyo SJ-301 device. The measurement results are shown in the gray rectangle. The surfaces of the model hob milling tools and measuring directions are shown in Fig. 13 [7, 27, 23].

In this part of the paper the roughness parameters for tooth-face as the most important surface of the tool were analyzed. In Fig. 28 the measurement results for measuring direction under the number 8 for the unworn uncoated model hob milling tool and in Fig. 29 for the worn-out uncoated model hob milling tools with the module $m = 3$ mm are presented.

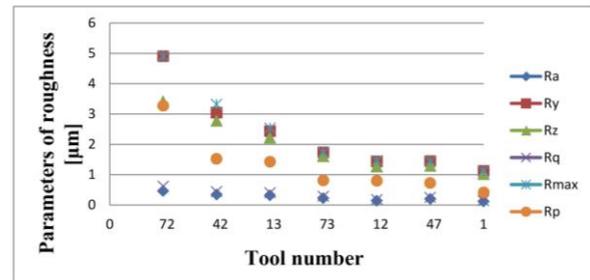


Fig. 28. Diagram of roughness parameters of the tooth-face for uncoated and unworn tools, module $m = 3$ mm .

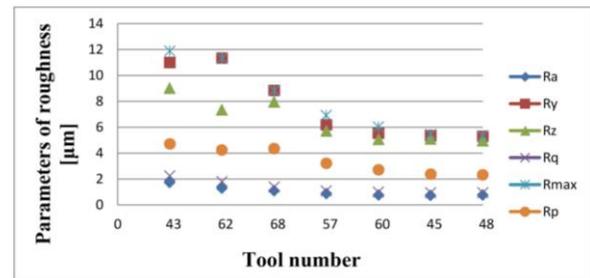


Fig. 29. Diagram of roughness parameters of the tooth-face for uncoated and worn-out tools, module $m = 3$ mm .

The results of the first part of the research are shown in diagrams, and a part of the results is given in this paper (Fig. 28 and Fig. 29). From the results of the tool with module $m = 3$ mm , the following conclusions can be made:

The roughness parameter R_a has a minimum value of $0.12 \mu\text{m}$ for the uncoated and unworn tool, while the largest measured value of this parameter is $1.74 \mu\text{m}$ for the uncoated and worn-out tool.

The roughness parameter R_y has a minimum value of $1.13 \mu\text{m}$ in the uncoated and unfinished tool, while the largest measured value of this parameter is $11.34 \mu\text{m}$ for the uncoated and worn-out tool.

The roughness parameter R_z has a minimum value of $0.97 \mu\text{m}$ for the coated and unworn tool, while the maximum measured value of this parameter is $9.02 \mu\text{m}$ for the uncoated and worn-out tool.

The roughness parameter R_q has a minimum value of $0.15 \mu\text{m}$ for the uncoated and unworn tool, while the maximum measured value of this parameter is $2.25 \mu\text{m}$ for the uncoated and worn-out tool.

The roughness parameter R_{max} has a minimum value of $1.13 \mu\text{m}$ for the uncoated and unworn tool, while the maximum measured value of this parameter is $11.88 \mu\text{m}$ for the uncoated and worn-out tool.

The roughness parameter R_p has a minimum value of $0.42 \mu\text{m}$ for the uncoated and unworn tool, while the maximum measured value of this parameter is $4.72 \mu\text{m}$ for the uncoated and worn-out tool.

Based on the results presented for the tool with module $m = 5$ mm , the following conclusions can be made:

The roughness parameter R_a has a minimum value of $0.24 \mu\text{m}$ for the coated and worn-out tool, while the largest measured value of this parameter is $1.09 \mu\text{m}$ for the coated and worn-out tool.

The roughness parameter R_y has a minimum value of $1.69 \mu\text{m}$ for the coated and worn-out tool, while the largest measured value of this parameter is $8.05 \mu\text{m}$ for the coated and worn-out tool.

The roughness parameter R_z has a minimum value of $1.67 \mu\text{m}$ for uncoated and worn-out tool, while the maximum measured value of this parameter is $6.86 \mu\text{m}$ for the coated and worn-out tool.

The roughness parameter R_q has a minimum value of $0.3 \mu\text{m}$ for the coated and worn-out tool, while the largest measured value of this parameter is $1.33 \mu\text{m}$ for the coated and worn-out tool.

The roughness parameter R_{max} has a minimum value of $1.70 \mu\text{m}$ for the coated and worn-out tool, while the largest measured value of this parameter is $8.05 \mu\text{m}$ for the coated and worn-out tool.

The roughness parameter R_p has a minimum value of $0.76 \mu\text{m}$ for the uncoated and worn-out tool, while the maximum measured value of this parameter is $3.46 \mu\text{m}$ for the coated and worn-out tool.

Based on the results shown, it can be seen that the parameters of roughness R_a and R_q are parameters whose results are fairly uniform and their dissipation is insignificant. In the roughness parameter R_p the dissipation is slightly higher than the parameters R_a and R_q , while the parameters of the roughness R_y , R_z and R_{max} are the parameters in which the largest dissipation of the results is observed.

The second part of the experimental research was carried out on eight single-tooth hob milling tools. From each of the eight subtypes of tools from the first part of experimental research, a tool with the highest arithmetic roughness was taken on that tool measurements of tooth-face were again performed. Measurement on tools were carried out in two directions, longitudinal (for module $m=3 \text{ mm}$ and $m=5 \text{ mm}$) and transversal (only for module $m=5 \text{ mm}$), (for directions of measuring see Fig. 13 [7, 27, 23]).

Based on the results presented in the second experimental research (Figs. 30-33), the following conclusions can be made:

The roughness parameter R_a has a minimum value of $0.15 \mu\text{m}$ for the coated and unworn tool with the module $m=3 \text{ mm}$ measured in the longitudinal direction, while the largest measured value of this parameter is $2.24 \mu\text{m}$ for the uncoated and worn-out tool with the module $m=3 \text{ mm}$ measured in the longitudinal direction.

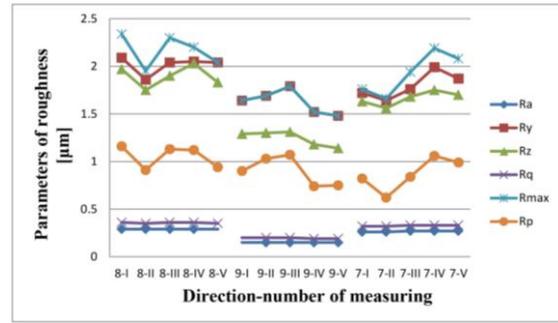


Fig. 30. Diagram of roughness parameters of coated and unworn tool with module $m=3 \text{ mm}$ measured in 3 longitudinal directions.

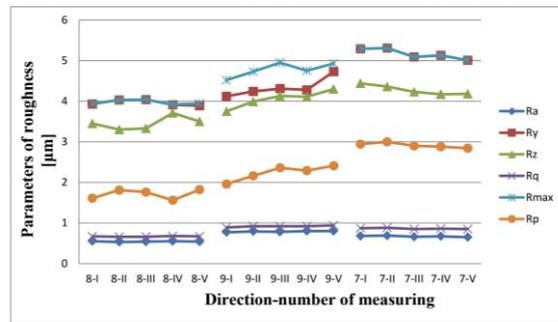


Fig. 31. Diagram of roughness parameters of coated and unworn tool with module $m=5 \text{ mm}$ measured in 3 longitudinal directions.

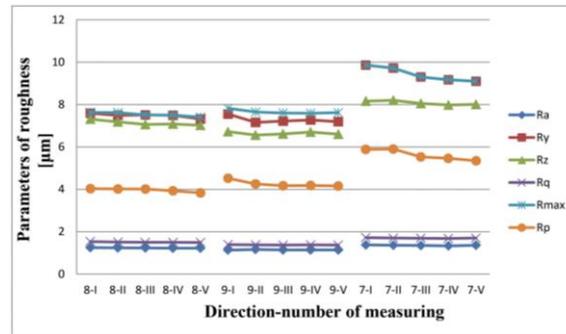


Fig. 32. Diagram of roughness parameters of coated and worn-out tool with module $m=5 \text{ mm}$ measured in 3 longitudinal directions.

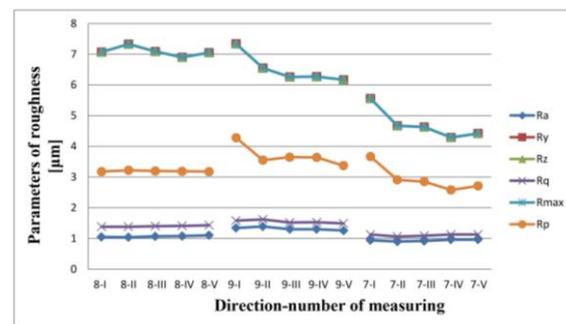


Fig. 33. Diagram of roughness parameters of coated and worn-out tool with module $m=5 \text{ mm}$ measured in 3 transversal directions.

The roughness parameter R_y has a minimum value of $1.48 \mu\text{m}$ for the coated and unworn tool with the module $m=3 \text{ mm}$ measured in the longitudinal direction, while the largest measured value of this parameter is $17.88 \mu\text{m}$ for the uncoated and worn-out tool with the module $m=3 \text{ mm}$ measured in the longitudinal direction.

The roughness parameter R_z has a minimum value of $1.14 \mu\text{m}$ for the coated and unfinished tool of the module $m=3 \text{ mm}$ measured in the longitudinal direction, while the largest measured value of this parameter is $13.66 \mu\text{m}$ in the uncoated and trapped tool of the module $m=3 \text{ mm}$ measured in the longitudinal direction.

The roughness parameter R_q has a minimum value of $0.19 \mu\text{m}$ for the coated and unworn tool with the module $m=3 \text{ mm}$ measured in the longitudinal direction, while the maximum measured value of this parameter is $2.79 \mu\text{m}$ for the uncoated and worn-out tool with the module $m=3 \text{ mm}$ measured in the longitudinal direction.

The roughness parameter R_{max} has a minimum value of $1.48 \mu\text{m}$ for the coated and unfinished tool with the module $m=3 \text{ mm}$ measured in the longitudinal direction, while the largest measured value of this parameter is $18.23 \mu\text{m}$ for the uncoated and worn-out tool with the module $m=3 \text{ mm}$ measured in the longitudinal direction.

The roughness parameter R_p has a minimum value of $0.62 \mu\text{m}$ for the coated and unworn tool with the module $m=3 \text{ mm}$ measured in the longitudinal direction, while the maximum measured value of this parameter is $5.99 \mu\text{m}$ for the uncoated and worn-out tool with the module $m=3 \text{ mm}$ measured in the longitudinal direction.

When measuring tools with the module $m=5 \text{ mm}$ in the transversal direction, it can be noticed that the parameters R_y , R_z and R_{max} are exactly the same. This characteristic is explained by the fact that the length of the measurement in the transversal direction has been changed, and the measurement results are only observed at one reference length.

5 Conclusions

The basic tribo-mechanical system during gear cutting by hob milling is made up of tribo-mechanical elements, work-piece, model hob milling tool and cutting fluid. The quality of the machined surface has a significant influence on the exploitation characteristics of tribo-mechanical elements.

Today, great efforts are being made to penetrate into the essence of the nature of the contact surface, and this is facilitated by new technologies and devices. The

consequences of tribological processes are the changes that occur on the surface layer.

Research of the topography of the characteristic surfaces of the model hob milling tools have been performed on one of the most modern devices Talysurf-Taylor Hobson and Mytutoyo SJ30 for testing the roughness parameters. In model researches the correlation, which has been verified in production conditions, between the roughness parameters could be predicted both for coated and uncoated tools, whereby high degrees of correlation have been accomplished. This can serve as a basis for drawing a conclusion that by following the roughness parameters on flank of gear teeth a moment of hob milling tool blunting can be determined. This is of great practical significance for axial tool feed.

As can be seen from the results presented the roughness parameters R_a and R_q are parameters whose results are fairly uniform and their dissipation is insignificant. For the R_p roughness parameter, the dissipation is slightly higher than the parameters R_a and R_q , while the parameters of the roughness R_y , R_z and R_{max} are the parameters in which the largest dissipation of the results is observed.

Based on the results of measuring the six most commonly used roughness parameters (R_a , R_q , R_z , R_t , R_{max} , R_p) or the entire experimental research in this paper it can be concluded that the topography of unworn coated model hob milling tools is better than the topography of worn-out coated model hob milling tools noting that the results of each of the parameters vary differently.

The basic roughness parameters of the lateral flank and tooth-face of the model hob milling tools cannot fully define the quality of this surface, so it would be necessary to use stochastic indicators of roughness for a more complex and better quality assessment of the profile of the tribo-mechanical element.

To complete the picture of the topography of the contact surfaces of the model hob milling tools, it is necessary in future investigations a precise definition of surface roughness through defining the distribution of the ordinates and the tops, the distribution of the inclination, the radius of the tops and recess of unevenness, carrying capacity curves of profile and others. A two-dimensional analysis can often be used as a process monitoring that is limited in scope, but provides a simple indication, regardless of whether the topography changes. For a more complete understanding, a three-dimensional analysis of the topography of the characteristic surfaces of the model hob milling tools is necessary.

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