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2D and 3D characterization of surface waviness; study and analysis of its effect on operational features

Doctoral (PhD) dissertation

AUTHOR'S REVIEW

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Scientific problem formulation

Studies of tribological systems are backed by major economic aspects. According to a study by the American Society of Mechanical Engineers, loss by friction and wear in the USA reaches 2% of the GDP. Earlier economic reports from Germany estimate the same at 4%, and it can be rendered probable that this ratio is even worse in Hungary.

Tribological phenomena are extremely complex; in addition, the quality of surfaces displaced under load must also be interpreted as a complex phenomenon including surface microgeometry differences, the physical and chemical status of the surface layer, such as plastic deformation during machining, the hardness of the surface layer, residual stress, texture, and chemical composition.

The two fundamental components of surface microgeometry are roughness with small clearance and waviness with much larger wavelength. Roughness and waviness have different geometric characteristics, their generation can be traced back to diverse reasons; however, both of them affect surface quality and operational features. A great number of excellent researchers and research groups are involved in the study of surface microgeometry, but it can be clearly stated that there is much less information available on waviness then on roughness. It can be stated both on the basis of the literature and my survey – to be considered as representative – that even today, industrial practice uses only some roughness parameters in the direction of height for surface tests and characteristic waviness parameters are required very rarely.

As a member of a research group involved in surface microgeometry and topography studies, I have investigated surface waviness for about two decades. I have published my results so far in the doctoral thesis defended at the Technical University of Budapest, in publications, and in (partial) research reports.

My earlier results were primarily related to 2D interpretation and evaluation. At the 1992 conference on *”The Newest Developments in Surface Topography”*, the necessity of applying a 3D technology was highlighted. According to opinions then formulated by researchers and industrial experts, the 3D interpretation of surfaces can yield information not available by the 2D technique. Many research works pointed out to the limits of 2D measurements in the 1990s, stating that only 3D tests are suitable for complete surface characterization and for exploring correlations between operational features and surface topography.

The topicality of the subject is also sustained by the new standards issued in the course of the past decade, which have solved a number of existing problems regarding the measurement and characterization of technical surfaces, but they raised new issues and contradictions as well.

The unresolved issues of waviness evaluation techniques, the suitability analysis of filtering methods to separate dislevelments of different orders, a 3D extension of the characterization of waviness, and the study of the connection between waviness and operation call for scientific research.

Obviously, the results of tribological research can play an important role in the technical equipment operated in the military. Taking them into consideration in design, manufacturing and operational maintenance may result in an extension of the uptime and an increase in the reliability of combat vehicles, weapons and other technical equipment frequently operated under extreme environmental conditions.

The dissertation presents my results achieved by the end of the first quarter of 2008. I intended my work to provide answers to important questions related to waviness. In the course of formulating them, further issues were obviously raised, further research objectives were outlined.

Besides practical applicability, the results of the dissertation also provide a basis for further research into waviness.

Research objectives

I set the following research objectives in the course of my research work:

1. Review the Hungarian and international literature and present the significance of waviness based on own measurements.
2. Process and analyze the present status of waviness evaluation techniques; explore unsolved or contradictory issues as detailed below:
   - Problems of separating waviness from roughness; state-of-the-art filtering methods, development trends.
   - Special 2D parameters of surface waviness used in standard and dominant industries.
   - The latest basic principles and evaluation techniques of 3D surface testing techniques; classification and mathematical models of 3D topography parameter sets.
3. Elaborate proposals for evaluation techniques on the basis of own measurements to ensure a clear characterization of waviness.
4. Study connections between surface waviness and operation in the following two areas:
   - Investigation and analysis of effects on microtopographic parameters to characterize operational features.
   - Study of the correlations between waviness and friction by experiments and by applying an analytical model.

   In order to be able to analyze the effects of the waviness component of the surface on microtopographic parameters describing operational features within broad margins, I also found it to be necessary to elaborate a new testing method.

On the whole, I envisaged to produce a dissertation to present the importance and evaluation techniques of waviness, as well as specific impacts on operation. It is to contribute to the elimination of deficiencies and contradictions related to interpretation and evaluation; to yield new scientific results both in terms of evaluation techniques and operation; and to provide a basis for conducting further research related to surface waviness.

Research methods

In the course of my research, I processed the related Hungarian and international literature; I presented my partial results in publications detailed among the References and at professional conferences.

In the course of the research work, surfaces were analyzed by two methods using instruments operating at the Donát Bánki Faculty of Mechanical Engineering and Security Technology of Budapest Tech (BMF-BGK). I conducted 2D and 3D tests primarily by a Mahr Perthen Concept type 3D stylus instrument; in some cases, I examined surfaces by a JEOL JSM 5310 type scanning electron microscope.

For the purposes of evaluating microgeometry and topography, I used the stylus instrument’s own software, the softwares developed by myself which are suitable for specifying the median line and motif parameters of waviness even for research purposes, the Surf3D microtopography evaluation software developed in cooperation by the Department of Machine and Product Design of the Budapest University of Technology and Economics and by BMF-BGK, with my involvement as well, the amplitude density spectrum (PSD) software developed by researchers at Budapest Tech, and a software developed within the National Institute of Standards and Technology (NIST) which is free to use and available on the Internet.

I studied the impact of surface texture on topography parameters characterizing operational features using mathematically produced waviness surfaces with the roughness topography of real surfaces superposed on them. Thus it was rendered possible to examine a great number of surfaces with highly manageable waviness characteristics in the longitudinal and amplitude directions, as well as to draw conclusions to be valid under the circumstances concerned. I used Visual Basic as a programming tool to produce the points of the surface generated; the Rhinoceros NURBS modelling software proved to be the most appropriate tool to display the points generated and the surface applied to it.

I generated surfaces of various wavelength and amplitude combinations to verify the applicability of the method, and I superposed the measured roughness topography of oriented (ground) and non-oriented (spark machined) real surfaces on them. In case of both roughness topography and the surfaces containing roughness and waviness as well, I determined the parameters characterizing operational features, drawing conclusions on the impact of waviness by a comparative analysis thereof.

I examined the interaction of surface waviness and the wear process by wear tests conducted in laboratory conditions. The ”Friction Wearing Tester” used for the experiments is a joint development by BMF-BGK and the Department of Machine and Product Design of the Budapest University of Technology and Economics, enabling tribological tests where the changes of numerous parameters (load, speed, stroke length, friction force, temperature) can be recorded in order to explore operational behaviour more deeply, and the wear and surface change process can be followed through. In my wear tests, I studied the dry friction of steel-ferrodo material pairs with different initial machining treatment, monitoring the friction behaviour of the material pair. I tracked developments in microtopography in the course of the wear process.

I used Persson’s analytic model to analyze the size of the real contact area, supporting my conclusions drawn from the wear tests with them.

A brief presentation of the research conducted chapter by chapter

In the **first chapter** I showed the topicality of the subject on the basis of literature research and my own earlier research results. This chapter also includes research objectives and a presentation of the methods leading to realize them.

The **second chapter** explains the significance of surface waviness, and highlights the errors that may be caused by disregarding waviness.

It can be stated from the analysis of the literature that waviness plays a considerable role in the qualification of technological processes because conclusions can be drawn on the manufacturing process from the surface waviness of the product concerned.

According to the literature, waviness frequently affects the operation of machine components displaced under loads, such as sliding bearings, conduits, arms locks, rolling bearings, and static seals. The **military significance** of rubbing machine components and related problems is verified by a summary study completed by USACE[1] for the U.S. Army, highlighting the tribological significance of the difference between the real and nominal contact area as determined by surface waviness and roughness.

Besides manufacturing and operation, the evaluation of waviness can provide information in the course of analyzing destruction processes.

I also supported the importance of the impact of waviness on operation by my own measurements, including the surface analysis of a clutch disk built in a tank. I verified, by evaluating the curves of a filtered profile without waviness and a real P profile bearing surface containing waviness as well that operational features are affected by waviness. So, by disregarding waviness, our conclusions on operational features can be mistaken.

According to an important statement in this chapter, in order to make waviness a tool to be properly usable in manufacturing supervision and diagnostics, the design of operational features, and the analysis of destruction processes, it is essential to solve open issues related to interpretation and evaluation technology.

In the **third chapter**, I provided a comprehensive overview of the evaluation technology of surface waviness on the basis of the international literature, and I worked out new proposals for the evaluation technology.

I presented various interpretations of surface waviness, developments in the standardization of waviness measurements, the present status of standardization and the tendencies expected.

Besides a general presentation of measurement possibilities, I provided evidence that the stylus instrument used by me is appropriate for the evaluation of waviness. I worked out proposals supported by measurements for the measurement parameters (sampling distance, evaluation length, evaluation section, evaluation area), which are not included in standard requirements, and the absence of which makes clear evaluation impossible in many cases.

I systematized processes for separating shape defects, waviness and roughness; I presented state-of-the-art filtering methods (e.g. morphological, wavelet, 3D filtering), and I performed their comparative analysis. I verified by measurements that the practice of separating roughness from waviness based on standards contains considerable error possibilities, and I made a proposal to solve this.

I summarized the standardized and the special 2D parameters of surface waviness; I presented the latest basic principles and evaluation methods of 3D surface tests; I classified the 3D topography parameter set. Annex 1 includes a detailed presentation of 2D and 3D parameters for characterizing waviness. I systematized and interpreted the rules of requiring 2D waviness in technical documents; I proposed considerations for 3D requirements.

In **chapter four** I presented my studies on the connection between waviness and operation and the results thereof.

I developed a new method for the correlations between waviness and the 3D parameters characterizing operational features, which mathematically generates the waviness component of surface microtopography. In case of the surfaces containing waviness and real roughness topographies, generated to verify the applicability of the new method, I studied the impact of waviness on operational parameters. Evaluation results are included in Annex 2. The new procedure developed proved to be a method suitable for such tests; I was able to draw conclusions on the connection between waviness and the parameters characterizing operational features.

I studied correlations between waviness and the friction coefficient through wear tests, using steel and ferrodo test pieces. I used Persson's analytic model to investigate the contact features of worn surfaces, and I used the results to support the conclusions drawn from experiment results.

[1] The United States Army Corps of Engineers

The **fifth chapter** summarizes research results in the form of theses and presents opportunities for utilizing the results.

The ”List of signs” enclosed summarizes signs mostly referring to microgeometrical and microtopographical features used in the dissertation; it includes the unit of measurement of the quantity indicated and its name in Hungarian and English (sometimes in German).

Summary conclusions

In industrial practice, the impact of waviness on operation is hardly taken into consideration as yet, waviness is rarely included in designs and requirements.

Waviness plays a considerable role in the qualification of technological processes because conclusions can be drawn on the manufacturing process from the surface waviness of the product concerned. I also verified by my own measurements that waviness frequently affects the operation of machine components displaced under loads, therefore it is necessary to be designed, required and measured. As a consequence of frequently extreme operational conditions, this statement especially applies to military technology equipment. Besides manufacturing and operation, the evaluation of waviness can provide information in the course of analyzing destruction processes, such as gun barrels.

However, in order to make waviness a tool to be properly usable in manufacturing supervision and diagnostics, the design of operational features, and the analysis of destruction processes, it is essential to solve open issues related to interpretation and evaluation technology.

One of the factors of fundamental importance of the process of waviness evaluation is filtering in order to separate roughness, waviness and shape defects. Researchers of this special area have worked out a number of filtering methods, only a small portion of which is standardized. In the framework of the research work, I analyzed the various filtering processes, explained their benefits and disadvantages, and touched upon their 3D applicability.

Based on the analysis of different filtering processes, I stated that there is no single process to solve every problem optimally due to the microgeometric and functional diversity of surfaces to be filtered; the most expedient solution must be selected depending on the actual task.

A development tendency regarding filtering is represented by the on-going improvement of median-line methods to eliminate the disadvantageous features of the most frequently used and standardized Gaussian filtering method, as also indicated by the ISO/TS 16610 series of recommendations issued in 2006.

Another tendency to be observed in the literature is an increasingly frequent application of completely novel evaluation techniques (morphological filtering, wavelet transformation). Such methods render it possible to analyze surfaces in more detail than ever before, vastly meeting the demands of scientific research and industries.

Waviness evaluation to provide clear and comparable results is hindered by the fact that certain measurement conditions (sampling distance, evaluation length, evaluation section, evaluation area) are not included in the requirements. I worked out proposals for them, supported by measurements.

ISO standards, draft standards, and industry requirements define a great number of 2D and 3D parameters of surface waviness. A summary presentation thereof is missing for research, industrial practice and technical education as well. Therefore, in the framework of this research work I systematized and presented in detail the 2D and 3D parameters to characterize waviness; besides, I systematized and interpreted the rules of requiring 2D waviness in technical documents; I proposed considerations for 3D requirements.

In order to explore the impact of waviness on parameters describing operational features, it is required to examine surfaces with various waviness characteristics. In practice, however, as waviness is generally caused by accidental technological disorders, it is difficult to manage the production of surfaces with previously determined waviness features; their production would only be feasible in the framework of a lengthy and costly procedure. Therefore it is expedient to apply a method whereby it is possible to produce and change the waviness component in a controlled manner. So I developed a new method to mathematically generate the waviness component of surface microtopography. I verified the applicability of the method by evaluations.

I conclude from the wear experiments conducted with steel-ferrodo material pairs that the waviness of the surface results in a reduction of the friction coefficient. I assume that this is caused by a smaller real contact surface. I studied the contact conditions of worn surfaces by Persson's model, and I used the results to support the conclusions drawn from experiment results.

New scientific results

THESIS I

When requiring roughness (R) parameters, EN ISO 1302 does not make it compulsory to specify the limit wavelength of filter λc to separate roughness and waviness, in the event that it was specified according to the EN ISO 4288 standard on the basis of previously estimated roughness parameters. I verified with the measurements in section 3.4 that it is not sufficient to refer to the standard: as much as several hundred per cent of differences may occur between the results of measurements conducted in accordance with the standard. Therefore I deem it necessary to require limit wavelengths in each case.

THESIS II

Wavelength evaluation is made difficult at present by the lack of registration of some measurement conditions. For the sake of clear evaluatability, I worked out proposals on the basis of my own measurement results and references in the literature.

a) The impact of sampling distance (interval) on waviness parameters was examined by the measurements presented in section 3.2.3. Accordingly, in order to avoid information loss as well as measurement and evaluation problems arising from an extremely large data set in the course of recording the waviness profile and the surface, the sampling distance is proposed to be selected as follows:
   - In case of $\lambda c \geq 0.25$ mm cut-off, the interval of $\Delta x(\Delta y)=10$ μm is sufficient,
   - In case of finely machined surfaces, where, due to the low values of roughness parameters the cut-off of the filter separating roughness is $\lambda c=0.08$ mm, the sampling distance needed is $\Delta x(\Delta y)=5$μm.

   I verified by measurements that in the case of the proposed sampling distances there is no information loss to affect the results of waviness evaluation.

b) As regards the evaluation section (lw) and evaluation length (ln) of waviness, there is a standard requirement only on motif evaluation. In the median line system generally used in practice, the currently valid EN ISO 4287 standard only requires that the evaluation length of waviness must consist of one or more evaluation sections; an evaluation section must be selected at the same value as the limit wavelength λf of the shape filter, but the value of λf is not specified. Based on the evaluation of my measurement results presented in section 3.2.4, I propose the following values:

– Waviness evaluation section: $lw=10\cdot\lambda c$,
– Waviness evaluation length: $ln=lw$ or $ln=2\cdot lw$.

The proposal is in line with the standard requirement, but at the same time it specifies the correlations required for evaluation but missing from the standard.

THESIS III

I introduced a new method for studying the correlations of waviness and 3D parameters characterizing operational features. By superposing real roughness topographies recorded by measurements to the waviness surfaces generated mathematically by the procedure developed, topographies with unevenness features of large intervals within a broad range can be created. This method greatly facilitates the examination of the impact of waviness to operational parameters, as the production of real surfaces with different waviness topographies would only be feasible in the framework of a lengthy and costly procedure.

I studied the impact of waviness on operational parameters (section 4.1.2) in the case of surfaces including waviness and real roughness topographies generated for verifying the applicability of the new method. In the cases studied, the impact of waviness on 3D parameters can be summarized as follows:

- Greater waviness (Wa/sRa>0.5) affects all topographic parameters except for Sdq and Stp, generally to a degree depending on amplitude.
- Considerable is the impact on the slanting index Ssk characterizing the height distribution curve and in connection with the operational feature of the surface, which already occurs in the event of slight waviness (sWa/sRa≤0.5).
- Though the figure of the bearing surface ratio Stp hardly changes to the impact of waviness, as a result of greater topography height, smaller changes will constitute altered operational features.
- The value of the parameter Sdq of average surface bending essentially depends on roughness only, the impact of waviness is negligible.
- No small amplitude waviness (sWa/sRa≤0.5) exerts a substantial influence on the parameters examined, except for the slanting index Ssk.

The new method proved to be suitable for examining the relations between waviness and 3D waviness parameters.

THESIS IV

I conducted wear experiments under identical operational conditions on steel- ferrodo material pairs in order to examine the impact of initial microtopography on friction. As a result of my investigations, I concluded that in the initial phase of the wear process, the friction coefficient greatly depends on initial microtopography: in case of a surface with smaller waviness and roughness features, a much higher friction coefficient could be measured than in case of topographies of larger roughness and waviness features.

Using Persson’s analytical model I stated that within the range of flexible contact, a smaller real contact area is established on a surface of greater waviness than in the case of a surface of smaller waviness.

Possibilities for using results; recommendations

In this dissertation, I provide a comprehensive picture of surface waviness for design, manufacturing and quality inspection experts by presenting the significance of waviness, by analyzing state-of-the art methods to separate unevenness features of different orders, and by an analytical presentation of the 2D and 3D analysis of waviness.

The results resolve the measurement engineering contradictions present in current standards as related to waviness, which do not render it possible, at present, to evaluate waviness to yield clear comparable results. The results of the dissertation provide a solution even in the areas of waviness evaluation technology not yet or not sufficiently regulated. Thus the results can be applied in the practice of waviness measurements and in the course of standardization as well.

The software developed to generate waviness surfaces can be used properly as a tool for studying the impact of waviness on operational features; it can be used for further research.

The dissertation highlights the connection between waviness and operation. The conclusions drawn on the basis of processing the literature and my own research results contribute to the fact that surface waviness receive a greater weight than today in regard to design, manufacturing, and quality tests in industrial practice as well as in the design, manufacturing and operational maintenance of the military technology equipment of the Association (North Atlantic Treaty Organization). A summary study completed by USACE (The United States Army Corps of Engineers) for the U.S. Army also highlights the tribological significance of the difference between the real and nominal contact area as determined by surface waviness and roughness.

I the course of personal consultations, military armament experts named several specific military application areas where surface microgeometry is prioritized in regard to operation. Some of these include the following, without striving for completeness:

- Certain structural components of military technology equipment operated on a ballistic basis (handguns and artillery equipment) are exposed to large heat load and friction stress in the course of their operation. The stress and operational conditions of the surface of locks and lock fittings (lock surface, rim embedding, the lock mirror of pin locks for present and future cannons) raise increased criteria for both design and manufacturing, requiring the design and evaluation of surface microgeometry containing waviness as well.
- The wear of the inside surface of gun barrels requires on-going supervision by operational maintenance; a qualifying tool can be a comprehensive evaluation of surface microgeometry (also extending to roughness and waviness).

There is no up-to-date and comprehensive training material available on the interpretation and evaluation of waviness and on the separation of unevenness features of various orders; the dissertation can be used as a resource both in civil and military technology education.