Recent trends in surface metrology

T.G. Mathia¹,*, P. Pawlus¹, M. Wieczorowski²

¹Laboratoire de Tribologie et Dynamique des Systèmes CNRS-UMR 5513, École Centrale de Lyon, 36 Av Guy de Collongue, Ecully, France
²Rzeszow University of Technology, Poland

A R T I C L E   I N F O
Article history:
Received 23 April 2010
Received in revised form 31 May 2010
Accepted 2 June 2010
Available online 11 June 2010

Keywords:
Surface topography
Measurement
Analysis
Applications

A B S T R A C T
This paper describes future trends in surface metrology. Measurement techniques are briefly mentioned. A special attention was paid to tactile and optical methods. Selected problems of surface topography characterization are described. The effects of sampling and filtering on surface topography representation are analysed. Structured surfaces are becoming both technologically and economically critical. Therefore their description is a problem of a great practical importance. Multi-process textures are very important from functional point of view. Various methods of their description are compared. Surface texturing as a means for enhancing tribological properties of frictional pairs started to be extremely popular from about last 10 years. The effects of surface texturing on improving tribological properties of sliding assemblies are analysed. The other influences of surface topography are mentioned in this paper.

© 2010 Elsevier B.V. All rights reserved.

1. Introduction

The last half century of geometrical aspects of surfaces metrology was extremely rich in events related to equipments design as well as data treatments dealing with parameters and standardized rules. Therefore it is difficult, pretentious and also dangerous to tempt the reliable prediction a fortiori to be counterpart of the 12th International Conference on Metrology and Properties of Engineering Surfaces. Specific contributions of British, German, United States of America, Russian, French and Polish schools caused considerable progress of techniques of measurement, methods of characterization with development of European Union and International standards.

Standardization processes will be probably increased in terms of methods of measurements and data treatments for specific applications due to the externalization, diversification of products and under contractor’s strategies. Particular attention is paid to creative process of new sensors for explicit applications in terms of better or less known transfer functions due to materials natures and range of topographical features. The scanning systems of different device designs and assemblies will be analyzed in context of precision and reliability taking into account especially the contributions of tribology. The new applications of surface metrology in traceability of surfaces, bionics, criminology and medicine will be analyzed.

2. Metrology

2.1. Measurement techniques

Despite a great development of optical and other techniques a tactile profilometer is still the most common roughness measuring device in mechanical industry. Yet, since Abbott and Firestone’s [1] construction from 1933 it has gone a long way. First of all modern software allows computing of approximately 300 parameters of roughness profile and dozens of topography parameters. Roughness can be measured on 200 mm length and 100 mm width with the deviation of guide equal to the fraction of micrometers, and further software support of accuracy can be applied. In this case the slide is measured by a laser interferometer and its errors are collected in the microprocessor’s system and used for the correction of indication. Besides the measuring instruments often offer simultaneously measurement of roughness and outline with greater range – even above 2 mm with 0.6 nm resolution. The interesting element of this device is a probe – magnetically fixed, which prevents damage (break), because during any impact or overload of the part, the diamond needle is separated from the body on a three points magnetic holder.

Additionally the probe is equipped with an AM transmitter and a receiver, which are used for communication with a central processing unit, and a simple memory chip. All of these assemblies of construction are together called an intelligent probe. In the memory the parameters of the probe are stored and sent to the controller after connecting to the holder. The memory contains also the data which are used to protect the probe during so called soft lowering. It limits the speed of the free falling of the measurement arm. Thanks

---

* Corresponding author. Tel.: +33 478433383,
E-mail address: Thomas.Mathia@ec-lyon.fr (T.G. Mathia).

0043-1648/5 – see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.wear.2010.06.001
to this, the probe does not strike at the end of a rapid fall, which could cause damage. Immediately after the probe is in contact with the lower measuring surface, the function of soft dropping is automatically turned off and the device continues the measurement. Next possible solution is the application of the measurement probe with bidirectional pressure force – up and down. It allows to measure, using the same probe, the roughness on the upper and lower surface of a hole, and in conjunction with an incremental linear encoder in a measuring column allows measurement of small inside diameters in a vertical axis. It is especially useful in the automobile industry, in the production of pumps and injectors, where without fears for probe damage CNC procedures to measure roughness, waviness and outline in small holes could be used (Fig. 1).

As a result from the analysis presented above, the principle of contact measurement and the methods of its making have not been changed for years. However development of microelectronics and computer techniques creates opportunities to increase the range and the resolution of devices and to introduce facilities for operators to reduce their chances to make mistakes. It seems likely that it will be the trend in development of stylus surface measurement in the next years.

Measurements based on a stylus profilometer in 3D surface topography of the surface are time consuming, which is a significant limitation. A possibility of overcoming this inconvenience is spiral sampling [3] (see Fig. 2).

Irrespective of the contact devices, constructions based on optical phenomena are being developed. Therefore the optical methods have been described in-depth in the scientific literature, e. g. in Bennett’s [5,6], Tiziani’s [7], Leonhardt’s [8] and others articles. New solutions have introduced CCD lines and arrays to detect the light signal, used i.e. in light scattering methods. These techniques can be used successfully in roughness measurements in preventive inspection, and their vertical measuring range reaches one micrometer.

Modern interferometers, used in roughness measurements, are systems which are applying white light. In contradiction to monochromatic light it distinguishes discontinuity of the surface for example deep valleys or high steps. The most popular interferometric measurement techniques are phase-shifting interferometry PSI, vertical scanning interferometry VSI and enhanced vertical scanning interferometry EVSI. PSI uses a monochrome light source and generally is applied to analysis of a very smooth surface, because this method is characterized by sub-nanometer resolution. On the other hand it suffers from phase-ambiguity problems, which limits PSI usability to a surface discontinuity not higher than \( \frac{\lambda}{4} \), where \( \lambda \) is the wavelength of the light used. Besides, the monochrome light source limits using PSI to ranges where continuous fringes can be obtained. In order to overcome this difficulty a new technique called Multiple Wavelength Interferometry (MWI) has been developed which has extended high-difference limitation successfully. In this method two wavelengths are selected, which allow the user to increase the dynamic range and at the same time to keep the resolution constant. Further increasing of the dynamic range is possible when white light is applied (VSI).

Then the continuity of fringes is not so crucial also, more important is finding a focus. The principle of vertical scanning is presented in Fig. 3. Unfortunately, the resolution of VSI is in the nanometers range, not in fractions of nanometers. The advantages of PSI and VSI are combined in the EVSI technique, also called white light interferometry with phase-shifting [9]. First of all every pixel is found in the optimal position of the objective for which this point of the surface is in the focus of the optical system, so in this position the distribution of intensity of the interference signal has a maximum. Secondly, to analyse the intensity around the point of focus a PSI technique is used, which allows to obtain better resolution than in VSI [10].

Interferometers and microscopes are combined in interferometric microscopy. Through that connection very good resolution and significant vertical range can be obtained. The interferometer is responsible for scanning on a nano scale, and the microscopy head is displaced on a micro-scale giving a vertical range even above 1 mm.

Descriptions of the operation of initial construction of scientific interferometric microscopes can be found in Wyant’s et al. [12] and Forman’s [13] articles.
Nowadays the interferometric microscope in English-language papers is treated as an optical profilometer which operates like a white light interferometer with a microscopy objective which increases the vertical range. Calling this device a profilometer might be misleading since during the measurement process the fragment of a surface is collected as opposed to acquiring individual profiles in a profilometer. During the operation of this kind of measurement system a lower beamsplitter is used to create a correlogram of each point of the surface, which next is collected by a CCD array (Fig. 4). By moving the objective within the vertical range, it can be found where the interference has maximum value. By monitoring of the position of the objective at the maximum interference value a topographic map is created. Analysis of a larger area is possible by applying stitching scans, thanks to this option the philosophy of this measurement may be compared to a multiprofilometer. The accuracy of stitching scans in the VSI causes a major error when this method is applied which can be compared to the difficulties in accuracy of the connection of profiles in a multiprofilometer. Errors occurring during stitching can deform the proper image of the measured surface as a whole [14].

Another disadvantage of interferometric microscopes is difficulty in measurement of roughness of thick (to hundreds of nanometres) transparent and semitransparent layers. In this case light is reflected from the top of the surface and substrate simultaneously and causes ambiguity of the signal [15]. Scanning of a large vertical range is based on the movement of the microscope head and precise analysis with the assistance of an interferometer [16]. In order to make vertical movement more precise a system with a reference signal is used [17].

Three interferometric objectives: Michelson, Mirau and Linnik described above are used in the interferometric microscopes. The Mirau objective is applied when at magnification about 50× the distance of operation is too small to separate the cube from the Michelson interferometer. Magnification above 100× requires an even smaller distance of operation, which can be ensured by Linnik construction. A beam splitter is located before the objective, and each split beam passes through a separate objective.

Another optical device used for roughness analysis is the scanning confocal microscope, which is one of the hybrid microscopes. Definition of a “hybrid microscope” or an “optical scanning microscope” applies to a device, which has the possibility to scan the surface and in consequence it can collect data like a profilometer. Descriptions of the foundation and operation of confocal microscopy can be found among others in Wilson’s [19] articles. The beginning of confocal microscopy in measurements of roughness has been described in [20], and further research was carried out among others by Perrin et al. [21], Tiziani and Uhde [22], and Molesini [23].

The principle of the operation of the confocal microscope is shown in Fig. 5. Light emitted from the source after passing through the optical path is focused on the analyzed surface. The reflected beam reaches to a diaphragm which transmits only focused light and to a photodetector. A vertical scanning system is moving the lens, which allows to analyze different height areas of roughness. That ability to distinguish height improves significantly the contrast and the lateral resolution in comparison with the classic optical microscope. Scanning confocal microscopes took advantage of the differentiation of depth and generating of surface image and reception of reflected beam is done by the same optical system. Like in the scanning method, the optical system generates a spot on a surface, and a reflected light beam is recorded by a point detector.

In the construction of a diaphragm of a modern confocal microscope a Nipkow disk with a series of spiral splitting small holes is used. In connection with a suitably prepared light beam (after passing through another Nipkow disk with microlenses) it allows a scan of the surface topography effectively.

Construction with the confocal head connected to the traditional profilometers instead of the contact head has become more popular in recent years. The light illuminating the surface is usually white light. The beam incident on the surface is split into its spectrum by the passive optical system. Only one chosen frequency which depends on the height of every point is focused on it and gives a sharp image of point on a photodetector. The photodetector is a precise spectrophotometer which allows to identify that wavelength which gives the information about the height of the roughness of the measurement. The scheme of this construction is presented in Fig. 6.

Like many other optical techniques the confocal system also has disadvantages. Some roughness causes a short lasting interruption in collecting the signal by the photodetector, which in turn produces sharp peaks and valleys which are not real. It results from the limitation that the illuminating beam can only resolve a slope with a maximum angle of about 90°, so points where penetration is not possible can be found. The corrupt part of this image can be corrected using filtration and interpolation which applies an algorithm for determining position with an ambiguous signal.

Other scanning microscopes are applied to analyze smaller roughness. Among them are two families of devices: scanning electron microscopes (SEM) and scanning probe microscopes (SPM) can be distinguished. Scanning electron microscopes are used rarely in the investigation of roughness whereas SPMs are becoming more and more popular.

The scanning tunneling microscope (STM) and the atomic force microscope (AFM) are the two most often used of the scanning probe microscopes. The fundamental application difference
between these two kinds of microscopes is that STM can be used only for conductive materials but AFM can be used also for non-conducting materials.

The atomic force microscope (AFM) is the most often applied form of the scanning probe microscope. This kind of microscope was first constructed by Binning et al. [26] as a combination of a STM and a profilometer. The principle of AFM operation is based on surface scanning using an elastic cantilever with a sharp tip. The tip is pressed down to the surface with a small constant force. The tip has height from a small part of a micrometer up to 2 μm and tip radius from 2 to 60 nm. Interaction of the tip and the surface is monitored by the reflection of the laser beam from the top of a cantilever on the photodiode detector.

First successful investigation using a self constructed STM was presented by Binning et al. [27]. The STM is based on the concept of quantum tunneling, where the conductive tip is brought very near to the sample surface (below 1 nm) and applied bias electrons from the sample can tunnel through the vacuum between sample and tip. This electron flow is termed a tunneling current. The value of the intensity of this current decreases exponentially depending on the distance between tip and sample. Constant value of the tunneling current is maintained by feedback which controls distance between sample and tip. The STM registers change of the value of the tunneling current with a constant distance or a change of the distance with the constant current.

Besides STM and AFM there are a lot of different types of scanning probe microscopes, which can be classified in four types: optical, thermal, electric and force. Some of them are not separate types of microscope, but only modifications allowed to use different physical forces.

The scanning microscope in recent years has been generally accepted. It is a tested and approved technique on the nano scale, which allowed to obtain very good vertical resolution. Serious problems appear only in the case of very rough surfaces and the necessity to use a larger vertical range. Microscope application can cause a little difficulty in the interpretation of results of measurement, especially when samples have inclusions or impurities on the surface, which characteristics are variable or can have an influence on response of instrument.

2.2. Limitation of existing techniques

Division of the optical methods is sometimes slightly artificial. Instruments which are the combination of several techniques have been created more frequently recently. It allows to broaden the measurement range significantly while keeping very high resolution. An example of this solution is the interferometric microscope. General treatment of optical methods is very cautious while on the other hand the classic profilometric methods are used confidently. This situation is not incidental and results from many factors, e.g. application of the optical methods is sometimes questionable due to the fact that for the estimation of the surface the whole mathematical models of the surface based on some assumption are used instead of using the surface itself. Moreover results obtained from the optical methods depend sometimes on physical properties of the surface. In metals for example reflectivity is significant in contrast to some other materials where it is much lower – sometimes it is so low that a large amount of the incident light penetrates the material.

In the case of the layered surface, multiple reflections on different layers may occur. Diversity of the penetrations influences the optical length path and changes test results. The presence on the surface of elements which randomly disturb the light path, for example small radius of curvature, microcracking or microholes might be another reason for the abnormality. Further the optical methods cannot always be compared with stylus methods, which sometimes makes comparison of test result impossible. On the basis of a number of comparative analyses some practical limitations for stylus and optical methods have been developed, as presented in Stedman’s [28] and Stedman’s and Lindsey’s [29] works.

Optical methods like stylus methods require the isolation of devices from the external environment. Both thermal effects and vibrations change influence on reliability of the result. Very careful cleaning of the sample surface is necessary from the point of view of industrial application.

3. Characterisation

3.1. The effects of sampling and filtering on surface topography representation

The process of analogue-to-digital conversion, called digitization amounts to the representation of the continuous analogue signal by discrete data. In the frequency domain the values of signal are recorded at equal intervals in the plane of the surface. This process is called sampling. If the sampling interval is too small, the data are highly correlated and a large number of data points are required to represent surface topography. If it is too large, the resulting data are highly uncorrelated resulting in the loss of surface spatial information (aliasing). In 3D stylus measurement the sampling interval should be as large as possible, because measurement time (comparatively long) depends on it. An assessment of surface topography by parameters is useful when long wavelength components are removed from the measured surface data. The unwanted elements of the surface geometry are commonly referred to the waviness, due to imperfections in the manufacturing process. A necessary preliminary to numerical assessment of surface profiles is to extract the frequency components representative of the roughness and to eliminate those that would be irrelevant. A Gaussian filtering technique has been adopted for the filtration of surface topography. The Gaussian filtering technique solved the problems of phase distortion but edge problems still exist in Gaussian filtration (marginal – running-in and running-out lengths, where roughness and waviness parameters cannot be calculated). The performance of the Gaussian filtering technique is affected by certain conditions, especially for surfaces having freak signals (outliers) such as grooves, scratches and scores. Multi-process textures are an example of such surfaces. The problem is that control of such surface texture requires a complementary response from surface metrologists. Without adequate measurement technique the control and hence any attempt to maintain quality is lost.
3.1.1. Sampling interval selection

Because long wavelengths exist on the surface after contact/wear, Whitehouse and Archard [30] proposed a sampling interval equal to distance at which the autocorrelation function decays to 0.1 value (correlation length). Several methods [31,32] for determining optimal sampling interval were suggested based on the principle that a tolerance between a parameter calculated from a sampled profile and the true value for the real surface did not exceed an acceptable limit. The main disadvantage of the above techniques is that spatial distortion due to discrete sampling is ignored. Wu [33] presented a method of obtaining the minimum sampling interval for a random profile of normal ordinate distribution. The proposed sampling interval depends on radius of the tip, correlation length and Rq parameter value.

Lin et al. [34] took into consideration the aliasing effect during 3D topography measurement by a stylus instrument. This method was based on areal spectral analysis. The Nyquist folding frequency (half of the sampling rate) was set at the position where the cumulative spectral power reached 95% of the total power. At the beginning, the sampling interval should be small, similar to the stylus tip size. Then sampling interval should be chosen with regard to the criterion presented above. The disadvantage of this method is that 95% cumulative power always exists. The other problem is that a large area should be mapped with a very small sampling interval before spectral analysis. Mainsah in his PhD work improved this method. He measured initially a profile, not a surface to determine the sampling interval so the preprocessing time was reduced. The chosen sampling interval was obtained by selecting the sampling interval at which 80% of the cumulative spectra falls within 1/8 to 1/3 of the Nyquist frequency [35]. The paper [35] is a continuation of Ref. [34] and Mainsah’s PhD dissertation. This approach was based on a profile spectral analysis. Its idea is that the major spectral power is represented by 80% of the cumulative power $f_i$. It should be located below the Nyquist frequency $f_c$. At first, a profile should be measured across the lay direction, using a very small sampling interval (smaller than radius of tip size). Then using different increments of sampling interval and corresponding data points from the original profile, the cumulative power of the subsections was calculated. The possibility was selected, for which the absolute value of the ratio $(f_0 - f_c)/f_c$ is the smallest, where $f_0 = f_c/8$.

Pawlus and Chetwynd [36] also initially analysed profiles, not 3D surfaces. They proposed a maximum sampling interval based on the shape of the cumulative spectrum graph. When the assessment length is sufficiently large, it is possible to obtain additional information about waviness content. The sampling interval was chosen equal to $1/2f_a$, where $f_a$ is the minimum frequency for which the vertical distance between the curve and the straight line describing (fitted to) its upper (almost linear) part does not exceed some fraction of the total power.

A specific investigation of determining a proper measurement area for cylinder liners, based on parameter variation, concluded that, while rougher cylinders required bigger evaluation areas, for smoother cylinders smaller areas were correct. It was proposed that initial measurements use the area giving the smallest parameter variation and then a smaller area might be studied using a smaller sampling interval [37].

Thomas and Rosen [38] proposed a tribologically appropriate sampling interval. The method took plastic deformation into consideration. A relationship was derived between the ratio of the critical wavelength to the topothesy, the fractal dimension and the material property ratio.

From investigations of simulated and real surfaces it was found that for a sufficiently small size of stylus tip 80% of cumulative spectra should be smaller than 1/3 of the Nyquist frequency $f_c$ (maximum sampling interval) for random surfaces. Minimum sampling interval depends on characteristics of the instrument, but bearing into mind flexible characteristics the proposal of Mainsah ($f_0 \geq 1/8$ of $f_c$) is sensible. So the proposal given in Mainsah’ dissertation is good [39]. It is also possible to select a sampling interval based on the autocorrelation function. A minimum sampling interval should be chosen by this way such that correlation between the measuring points ought to be smaller than 0.85 (it roughly corresponds to $f_0 = 1/8$ of $f_c$). However the maximum sampling interval should be selected in such a way that the parameter determining the shape of the autocorrelation function in its initial fragment should be possible to determine [39]. If the sampling interval is too large, the shape of the cumulative spectra will tend toward a straight line with no obvious “knee” (see Fig. 7). So the analysis of the cumulative spectrum graph can be helpful in diagnosis if the sampling interval was selected properly [38,39]. Paper [40] was focused on the evaluation of a general methodology for sampling in relation to the variation of the surface topography. A global and local sampling strategy proposed can be used to optimize the measurement time and confidence in measured surface topography parameters.

3.1.2. Filtering of surface topography

In order to overcome the problems with Gaussian filtering a regression filter that works without running-in and running-out lengths was developed [41]. Its algorithm is based on the internationally standardised Gaussian filter. Spline filters also work without marginal lengths. Non-periodic spline filters are useful in the case of filtering non-periodic profiles, like roughness. The spline filters discussed in ISO are based on natural cubic splines [42]. The behaviour of the proposed spline filter should be similar to that of a Gaussian filter. Numada et al. [43] proposed a high-order profile spline filter. Short calculation time is its advantage. An areal spline filtering technique was proposed in paper [44]. Differences between parameters obtained using a regression filter and the ISO 11562 filter were studied [45]. It was found that deviations of roughness parameters were comparatively small (smaller than 3%). The differences in the profile mean lines occur in the marginal areas. So the differences could be higher when the assessment length consisted of a small number of cut-offs. The changes of the waviness parameters caused by various analysed filtration methods were bigger than those of roughness parameters. The spline filters are the alternative. However errors in roughness parameters computations after using a spline filter were bigger and computation time higher than after using a Gaussian regression filter.
Therefore the Gaussian regression filter was recommended. The tendency found during profile investigations was confirmed during Gaussian regression filtering of 3D surface topography. Changes of surface were bigger for larger initial surface wavelengths. No dependencies were found between measuring areas and values of parameter errors. However changes of surface parameters were not big: $S_{Ra}$ to $6\%$, slope to $1\%$ [46].

Although the fine marks of multi-process texture fall well within the accepted bandwidth for the sample length (cut-off) the scratches do not. They are too wide. For these surfaces, the distortion after Gaussian filtering can be also big. One possibility to overcome this problem is the increase of cut-off from 0.8 to 2.5 mm. Other methods are to establish other filter kinds. From the above presented reasons, $Rk$ filtering technique using two-step Gaussian filtering is recommended by ISO (ISO 15656-1). However it cannot restrict the influence of freak characteristics of the peak part of the profile. In addition, the edge problems exist in it. Then, the Gaussian robust profile filtering technique was established [41]. A filter is called “robust” if the freak values do not lead to the distortion of the filter mean line (waviness profile). With robust algorithms even highly stratified surfaces can be filtered without the distortion of functionally relevant surface features (laser spots, honing valleys or EDM craters). It is important that the robust filters should behave neutrally for surfaces of normal ordinate distribution. Robust Gaussian filtering techniques proposed in Ref. [41] used a Tukey weight function to perform the robust filtering. Several other typical robust weight functions [46] were compared in Ref. [47]. A novel Gaussian filtering algorithm was proposed and analysed with computer simulation and a case study. A robust Gaussian filtering method was proposed and used to characterize the 3D surface topography of ultra-precision machined surfaces. Cubic B-splines and M-estimation were used to make the method reliable and robust [48]. Several typical robust weight functions were adopted [45]. The valley suppression $Rk$ filter as well as envelope and closing filters were also included. The results of filtration of deterministic and random 2D profiles and 3D surface topographies of symmetric ordinate distributions were analysed and compared to those obtained after using a Gaussian regression filter. In these cases the waviness and roughness parameters using Gaussian robust and non-robust filters should be identical. The computer generated 2D profiles and 3D surface topographies having triangular scratches and measured stratified surfaces were also subjected to filtration. It was found that the choice of the filter should be a compromise between the distortion of a profile of a symmetric ordinate distribution and of a profile containing a freak. The surface topography distortion and computation time were compared. Based on the comparison results, some digital filters were recommended. The Tukey method (4.4) showed good performance for stratified and Gaussian surface topography. The other proposed functions are Hampel (1.5, and 3) and Andrews (1.5) [45]. Fig. 8 presents the view of a plateau-honed cylinder surface and one profile from this surface unfiltered and filtered using different functions (waviness profile). The paper [49] presents a new approach for the separation of surface topography deviations by fitting a reference surface that remains robust against deep grooves. The proposed least square method was compared with robust Gaussian regression filtering.

The envelope method is another possibility. When an upper envelope is used, the surface properties depend on the peak surface part. When a circle is used its radius of 25 mm corresponds to a cut-off of 0.8 mm. Whitehouse and Torrance [50,51] found that this method is good for the analysis of multi-process texture. The filtering procedure of 3D surface topography is time consuming. The authors of Ref. [52] presented the possibility of decreasing computation time. Morphological filters were developed for scientific usage. There are two basic types of envelope filters namely the closing filter and the opening filter. These filter kinds are based on erosion and dilation. When spherical balls of radius $r$ are used, the erosion is the locus of the centre of an ideal tactile sphere, with radius $r$, rolled over the surface. The sphere rolling underneath the locus of the sphere of the dilation is a morphological operation called erosion. Closing is the simplest morphological filter and consists of a dilation followed by an erosion (opening consists of an erosion followed by an dilation). They were described in Refs. [53–57]. Closing filters are suitable for the analysis of stratified surfaces [55]. An interesting attempt to use the wavelet transform to separate features of different scales relevant to manufacturing process and functions was presented in paper [58]. The main advantages of the wavelet transform over other existing signal processing techniques are its space-frequency localization and multi-scale view of the components of a signal. In addition, it is a powerful tool in the characterisation of the local morphology by pinpointing the local motif using the modulus and the phase of the wavelet transform so the roughness and waviness components can be quantified [59]. Filtering by wavelet transform of three-dimensional surface can be found in Refs. [60–64].

### 3.2. Standardisation

In current topographic analysis of the surface more 3D parameters are used for the evaluation of the surface. The initial suggestion to limit description to 14 or 17 definitions has been superseded a long time ago, we can gain an impression that “parameters fever” [65] has reached this area too. As well as the parameters which are
treated in standards, special parameters, which are used for specific applications also occur. Some examples will be given later.

3.3. Description of structured surfaces

Surfaces with a dominant deterministic feature pattern are considered to have a defined structure and are termed “structured surfaces” [66]. All structured surfaces are specifically designed to meet specific functional requirements, for example minimizing friction, wear or tendency to seizure. Traditional concepts in surface metrology, such as roughness, waviness etc. are not useful for the description of such surfaces. Their characteristics are statistical (mean, maximum, and range) and derived from the individual values (feature depth/height, width, length, and volume area) or relationship between features (distance between them, pit-area ratio). To identify features on a surface, an automatic method is required to segment the surface into regions of interest followed by techniques to identify the geometric primitives and analyse their departure from the nominal as a function of their spatial arrangement. It is useful to classify structured surfaces into two classes based on their geometric form Refs. [67,68].

3.3.1. Structured steps

These surfaces include steps edges and facets. Fresnel lenses are examples. The analysis of these surfaces is based on the detection of edges using edge detection filters such as Sobel filters.

3.3.2. Structured patterns

These surfaces are made from repeated patterns over the texture. Textured surfaces with dimples created to improve tribological properties of sliding pairs are examples. Characterisation of them entails analysis and identification of the departure from the nominal geometry of the basic repeat unit and analysis of the distribution and spacing of the repeat unit. The approach used to these surfaces is analyzing the surface autocorrelation function and then applying pattern analysis (segmentation) to the autocorrelation function. The segments around the origin of the autocorrelation function provide information on the average basic repeat unit and the relationship of the origin segment with its neighbouring elements of the tessellation pattern [67].

For example the hard drive industry uses a special area (a series of laser ablated holes) on the hard disc to park the hard drive head. Segmentation is used to define the extent of each hole; then the distance between two adjacent holes C and the distance between two adjacent rows of holes D and holes density are easily calculated (see Fig. 9). Then the mean distances as well as the maximum, minimum and average depth, diameter of the holes and pit-area ratio were computed. The diameter is calculated as the best fit least square circle fitted to the segmentation boundary of the holes. Till now parameters characterising textured surfaces were calculated manually; the segmentation technique with feature analysis offers the possibility of fast automatic calculation.

3.4. Characterization of multi-process surfaces

Most engineering surfaces have height distributions which are approximately Gaussian. However multi-process texture is more important from a functional point of view. A plateau-honed cylinder surface is the typical example. It consists of smooth wear-resistant and load-bearing plateaux with intersecting deep valleys working as oil reservoirs and debris traps. The roughness of multi-process surfaces is difficult to characterise. Sets of special parameters, embodied in two ISO standards, were developed to describe the material ratio curve. Fig. 10a presents parameters described in the ISO 13565–2 standard. Fig. 10b shows parameters from the ISO 13565-3 standard. The method described in the ISO 13565–2 standard is commonly used in European industry for plateau-honed cylinder surface topography characterization. Parameters, like the reduced peak heights Rpk, the reduced valleys depth Rvk, the core roughness depth Rk, and material ratios determined by the straight line separating the core roughness from the material side (Mr1) and free from material side (Mr2) can be calcu-
dependencies between height parameters: (a) Rvk and Rvq and (b) Rpq and Rk [78].

Fig. 11. Dependencies between height parameters: (a) Rvk and Rvq and (b) Rpq and Rk [78].

The ISO committee incorporated another alternative way of characterising a two-process surface [76,50] with a sound theoretical basis. Honing is a process which is known to produce a Gaussian distribution of surface heights. A process of coarse honing followed by fine honing will superimpose one Gaussian distribution on another. If the resulting cumulative distribution is plotted on a normal probability scale, it is shown as two straight lines (Fig. 10a). The straight line is fitted to the central 40% of the material ratio curve. The distance between the intercepts of this line with the height axes is defined as the Rk parameter. This arbitrary construction is in general use in Europe and seems to produce satisfactory results. The parameter Rk is a measure of roughness height after a running-in process, but the parameters Rvk and Mr2 are measures of capacity of oil accumulation in the honing valleys. Decreasing Rk, oil consumption decreases, but increasing Rvk the seizure resistance increases. The honing process could be controlled by Rk parameters according to Nielsen [70]. In Zipin’s opinion [71], this approach can be misleading since the material ratio curve of normally distributed random surface profiles exhibits a variation of slope. In addition some parameters found in this standard are non-synonymous [72]. It is always difficult to achieve all the parameters from ISO 13565-2 standard within a certain range and the operator’s experience is relied upon. In practice, Mr2 is considered as an important parameter among the bearing area parameters and is assigned a higher weighting of 50%, while Rk, Rvk, Rpq and Mr1 are assigned 30%, 15%, 4% and 1% respectively [73]. The work described in Reference [74] is an investigation carried out to identify the significant honing parameters and their values for different honing operations. It was found that honing pressure played an important role in controlling the finish. The Ra parameter is important in all stages of the honing process, while it can be replaced by Rk in finish honing and plateau honing operations. The Mr2 parameter is to be controlled in the finish and plateau honing operations. Data mining approach was used in the investigation to select significant honing parameters and their levels considering two important bearing area parameters Rk and Mr2 together to achieve the required surface topography [75].

The statistical connections among parameters from the two analysed standards were analysed using linear correlation coefficients [78–81]. However it is hardly possible to find what parameter set is the best. For example, it was found that within the Rk family, the independent pairs of parameters were Rpq, Rvq, Rk and Mr1, Rpq, Rk and Mr2 [78]. The Rk parameter was correlated with Rpq (ρ = 0.72), but correlation between Rm1 and Rm2 was the greatest (ρ = 0.97). Within the Rq family, the absolute values of correlation coefficients were smaller than 0.5. Between the parameter families, Rm1 and Rm2 were highly correlated with Rmq, and the respective peak and valley parameters are also highly correlated (see Fig. 11).

Other parameters from the Abbott curve exist in the CNOMO standard. These are: the parameter Cr: running-in criterion calculated between the material ratios 45 and 99% and Cl: lubrication criterion calculated between the material ratios 15 and 75% and Cl: lubrication criterion calculated between the material ratios 45 and 99% [80].

Image-processing technique has also been used to characterise plateau-honed surfaces [81–83] but it is not used in industry to control the honing process.

4. Applications

4.1. The effect of surface texturing on improving tribological properties of sliding assemblies

Surface texturing as a means for enhancing tribological properties of frictional pairs is well known for many years. However it
The main objectives in developing this technique were: productivity comparable with that of conventional honing or plateau honing, a high degree of reliability of the process itself and in mass productivity comparable with that of conventional honing or plateau honing, and a high percentage contact area of cylinder liner is needed. It can be done by reducing the base honing valleys depth (slide honing). The main objectives in developing this technique were: productivity comparable with that of conventional honing or plateau honing, a high degree of reliability of the process itself and in mass production conditions, long tool life, minimum deformation in the honed surfaces, i.e. minimal dislocations in the boundary layer and the creation of a uniform and consistent surface over the whole cylinder bore [92]. The increased presence of cold work material on cylinder liners due to the introduction of diamond honing is undesirable. However in the engine tests, the diamond honed liners showed good performance [93]. The relative basic honing fluting with conventional surfaces (honing angle about 45°) was considered to be sensible for many decades. However, it was found that the reduction of wear and scuffing tendency can be achieved by altering the geometry of basic honing valleys. The honing grooves were arranged in the direction of the piston in an elongated spiral (helical honing–honing angle about 140°) [94]. Various endurance tests on 6-cylinder production engines of up to 3000 running hours have proved the advantages of helical honing. The wear in the reversal zone was reduced by approximately 40% as compared to the previous production plateau honing process [95]. The other proposal is the creation of cylinder surface structures by a modified honing process followed by laser texturing. This represents a very promising approach for reducing both wear and friction losses without an increase of the oil consumption. It was found that volumetric wear of the laser-textured surface was reduced in comparison to the standard plateau-honed surface [96]. Laser texturing on a cylinder surface was used in order to minimise risk of seizure [97]. Another possibility is the creation of a deterministic cylinder structure by laser honing. It ensures 2–3 times smaller oil consumption and smaller wear of piston rings and cylinder during test of 330 h duration in comparison to plateau honing [98].

Fig. 12 presents schemes of different cylinder liner surfaces. Fig. 13 shows the effect of surface texturing on volumetric wear of cylinder from internal combustion engine.

The other possibility is the laser texturing of piston rings. Experimental tests, which were performed on a laboratory reciprocating test rig showed that a friction reduction of up to 25% can be obtained by partial texturing of cylindrical face rings in comparison to untextured rings of barrel shape [100]. It was found that partial laser texturing piston rings produced up to 4% lower fuel consumption in an internal combustion engine, while no traceable change in the exhaust gas composition or smoke level was observed [101].

The applications of texturing include also: piston pin, disk brakes, thrust bearings, journal bearings, mechanical face seals, gas...
seals, hard disk sliders, magnetic tapes, machine tools guideways and other elements. One can find recent publications presenting profitable effects of surface texturing on seizure resistance in Refs. [102–104] transition between fluid and mixed lubrication in Refs. [105–107] and wear resistance in Refs. [108–110].

The case of texturing usually requires multi-scale analysis, therefore frequently different techniques should be used [111].

4.2. Other applications

The topography of a surface is commonly used to analyze surfaces after different types of machining [112,113]. It is treated as a representation of the manufacturing process, so it represents what was occurring with the tested sample. Topography of the sample could be used for typical or unconventional machining, to optimize the machining and the tools parameters. 3D surface topography has found an application in the surface analysis after less conventional machining, however this classification is flexible, because it can happen that something that was treated as unconventional is nowadays thought to be traditional. Nevertheless, the examples presented below have not been in common use. At first the examples could be coupling standard methods of machining modified by additional conditions e.g. diamond turning combined with ultrasonic [114] or elliptic vibrations [115], which are used to obtain a mirror surface, or abrasive machining with positive influence of cavitation [116].

Topographic analysis of the surface is also used in plastic forming, mainly in the automotive industry. With use of this method the metal sheet of a car body is tested at different stages of production (after rolling, stamping [117]) and as a complete object (analysis of the influence of the roughness and waviness of the surface on quality of the paint coat and appearance of the final element) [118]. Application of topographic analysis of the surface in the production of the metal sheet of the car body has become more meaningful recently. New methods of the production of the rolls, or more precisely the modifications of their surfaces have been invented. They are used in rolling elements, which are covered by coats, paints, lacquers in a further operation of the processing. It allows to improve their frictional properties and thus to improve adhesion of the covering element to the substrate through giving coating elements abilities to keep the coat stable.

Roughness of the surface is connected with the result of testing materials. It influences impact resistance (in the investigations of Lee and Mills for injected polyester [119]) and roughness of the surface changes under the influence of sample deformations [120].

The next property of the materials, which is connected with morphologic surface analysis is hardness. Hasche et al used an AFM to measure the geometry of a microindenter [121]. The result of hardness measurements (especially on micro-scale) was compared with the topographic evaluation of the indentation produced by the indenter which was measured by stylus profilometer [122,123].

The results draw conclusions that the second method gave a better picture of the materials properties. Such analysis makes possible visualization and precise quantitative evaluation. A topographic picture of indentations does not always enable the visualization of cavities in their lower parts, therefore inversion of data is commonly used.

Topographic analysis of the surface is used to test its corrosion resistance. Fig. 14a shows the picture of the topography of a surface, on which deep valleys occur. Because of them the surface has a tendency to corrosion. Fig. 14b shows a surface with a nearly normal distribution of roughness where this problem does not occur. Structures with deep valleys, with traces of machining and without the possibility of precise wash out have a tendency to corrosion. In this case, red fields are up to 7 mm above mean plane, while blue ones are 3 mm below.

Fig. 14. Image of surface with tendency to corrosion (a), without tendency to corrosion (b) [124].

Topography of the surface was used and is still used in other disciplines of science, absolutely unrelated to engineering. Examples can be taken from biology, medicine and chemistry. In zoology the surface of animal tongues has been analyzed, in order to understand the mechanism of food transport at an initial phase. Results of this kind of testing e.g. tongue of Talpa europaea [125], mouse [126] and eagle [127] have been published. An image of a fragment of the tongue of an eagle obtained by SEM is presented in Fig. 15.

Unusually interesting tests have been realized in the food industry, by the investigation of the connection between topography of chocolate and its visual aspects [128]. Additionally the dependence of roughness on temperature of chocolate fracture has been tested.

Research applications of surface topography in medicine and bioengineering can be without hesitation admitted as being a real triumph of the end of the last millennium and the beginning of the new one. A review of applications from bioengineering has been described in Ref. [129]. In the case of the tooth: from one side there is an analysis of the roughness of surface, and from second a lot of

Fig. 15. Section of eagle tongue [127].
An oral cavity is continuously polluted by different microbes. Most of these microorganisms can survive inside, only if they succeed in adhering to the surface and nesting (or living) in its roughness. This is the reason why roughness of the surface is so significant. Quirynen et al. [130] showed that increase of the roughness to about $Ra = 2\, \mu m$ cause significant intensification of bacteria colonization. In this regard value $Ra$ below 0.2 $\mu m$ is considered to be satisfactory. Therefore studies of patients at different ages – from children up to aged people – are taken and comparative analyses are performed.

These researches have been done in order to define proceeding changes on the tooth surface as result of caries. An interesting observation is that caries does not start when a tooth is rough but when it is smooth. When caries appears, it should be eliminated and a filling should be put in. At this time the morphology of the tooth surface is tested after drilling. Moreover the influence of chemomechanical eliminating of the caries is studied on the topography of the surface of the ceramic dental materials. A noteworthy discovery is that, the hygiene of the oral cavity does not influence teeth roughness. Slop and Arends [131] showed that using toothpaste or even a dental floss does not change the value of $Ra$ and this parameter could be even increased by using a toothpick frequently. If caries could not be cured by conventional therapy, other less pleasant techniques should be applied, namely dental extraction. If the patient wishes it then the implant is replaced.

Bones and implants surface analysis are another important medicine application, since roughness of the implants surface has a notable influence on the force of the connection and the reaction of tissues in the joint area between bone and implant, and even on behavior of germs in bone tissue. Methods of the roughness analysis of the implant vary from stylus profilometer through optical methods to scanning microscopy. Especially the influence of the surface topography on the adhesion of human bone cells to artificial elements (implants, manufacturing usually from titanium [132]) is investigated. Analysis concerns both the bones of the jaw (dental implants) described above as well as the bones of limbs (hip prostheses). In stomatology specially the influence of the roughness of implant on the binding force is examined [133]. Moreover attempts are made to define the optimal roughness of the implant surface in order to obtain the best tensile strength of the whole set and general operation of bite elements. Implants are used not only in stomatology but also widely in surgery. Also in this case the influence of roughness on the correct operation of the implants and their connection with bones was tested [134].

The possibility of manufacturing the objects with predetermined roughness is especially significant, since an important connection between topography and calcium deposition exists. Similarly like the implants in stomatology, hip joint endoprosthesis plays an important role in surgery. Hip joint replacement, that is surgical intervention, is connected with placing foreign matter into the environment of the human body. It is based on the assumption that the implant will meet biomechanical requirements for a long time and at the same time it will stay biologically neutral. Proper functioning of the hip joint implant includes three independent issues: fixation of the acetabulum in pelvis bone, reliable working of the joint of the head and the acetabular cup, and placing the stem in the femur. The Endoprosthesi problem is important since the human population is ageing, so an increasing number of people require this kind of operation. At the end of the 90s of the last century about 250 thousand of this kind of operation was carried out just in the countries of old European Union. It should not surprise anybody that many articles on this topic have been published. Blunt and Thomas analyzed roughness of the endoprosthesis elements of hip joint in order to estimate its wear [135]. The knee prosthesis is equally important. Charlton and Blunt described the surface topography of the polished element which is used as a knee implant [136]. Hilerio and Mathia concentrated on a similar subject area [137]. A view of a knee prosthesis is shown on Fig. 16.

Analysis of human skin surface is a very popular usage of the topography analysis in medicine especially in dermatology. Rough skin and wrinkles are easily visible negative elements of appearance so roughness measurements of skin are absolutely essential in the cosmetic industry. Such analysis is made to verify the efficiency of particular creams used to improve the skin conditions [138]. Here – as in mechanical engineering – researches on those parameters that allow effective and fast qualitative and quantitative analysis of the specific qualities are taken up [139]. Topography of the human skin surface is measured by optical or stylus methods from replicas [140]. An interesting method of skin topography analysis in vivo is Fast Optical in vivo Topometry of Human Skin (FOITS), it is developed on the basis of a similar method from the automotive industry [141]. This is a non-contact method of obtaining data about the topography of skin. The system includes a projector and a video camera angularly fixed in a triangular system. Comparative test of FOITS and laser profilometry showed agreement [142]. Measurement is most often made at different stages, before application of the cosmetically active substance, in the course of using it and after finish in order to show the influence of the treatment on the smooth surface. Comparative tests of women in different regions of the world are carried out in order to discover regional and genetic aspects of the visible symptoms of advanced age [143].
It is worth showing some more examples of surface measurement application. Let’s start with asphalt pavement analysis [144]. In this case roughness conventionally includes wavelengths in the range 0.1–100 m and amplitudes from 1 to 100 mm. Lower components are called texture macro and micro. Pavement roughness has influence on the vehicles using it, therein on correctness of tire functioning, their friction and vibration [145]. Pavement conditions affect also the distribution of stresses in the subsurface layer, and this is the result of e.g. roughness of the road-metal used [146]. Different techniques are used for asphalt roughness analysis. A review was published in article [147] and it refers to highways. Therefore – similarly to machine engineering – profilometers with different accuracies depending on the requirements can be used and optical systems instead of stylus heads, for example autofocus laser systems or sensors dependent on sonic wave reflection.

Another possibility is using an acoustic transducer or an image analysis system [148], which can be for example an optical scanner. An image of the surface topography of asphalt pavement obtained with the help of this device is shown in Fig. 17. In this case, red fields are up to 7 mm above mean plane, while blue ones are 3 mm below.

Equally important as a road in asphaltic concrete are roads of steel, i.e. rails. Papers [145,146,149,150] are devoted to their roughness analysis. Especially important are places, where violent braking – contact of the brake block with the rail occurs. This causes formation of roughness, which has an influence on the phenomenon proceeding on the surface and on the subsurface layer of the rail during its contact with the wheel band. Just as a result of roughness local exceeding of boundaries conditions of mechanical strength and cracking of the material can occur, which can have an effect with very serious consequences including accident. It was observed that roughness of the wheel band is one of the factors, which cause locomotive derailment during switching tracks, if the value of the roughness parameters after switching does not meet the requirements.

The next important branch in this context is cloth and material manufacturing, where roughnesses are analyzed especially when special requirements are placed on them, for example keeping warm or ensuring the aesthetic properties of a car interior. In such tests stylus profilometry does not find an application, whereas optical techniques are used for example a laser sensor [151]. In sports popularity was gained by an analysis of the roughness of the underside of skis [152]. Fig. 18 presents the surface of the underside of cross-country (a) and downhill (b) skis. In this second case as a result of contact of skis with snow at high speed a lot of heat is produced and snow is melted, hence grooves should quickly remove water in order that the speed of the downhill run does not decrease.

Surface topography analysis is often used in the paper industry. Because of the delicacy of the investigated surface stylus measurements are replaced by other techniques mainly based on light scattering, although acoustic sensors [153] or AFM are also used. These methods allow for testing of paper for special applications, analysis of old prints and marks of physicochemical impurity or analysis connected with the deposition of a drop of ink from the printer. Roughness of the paper has influence on the deposition of the ink component, which causes non-uniformity of colour printing [154]. On paper with higher roughness uniformity and quality of printing is worse. Fig. 19 shows a surface of rough paper. Application of the topography parameters of the surface allows to ascertain
that surfaces with similar values of some parameters may have totally different appearances and performances.

On banknote surfaces except overprint also three-dimensional special marks are plotted, which make it difficult to counterfeit banknotes and allow to evaluate their authenticity. An image of the 50€ banknote fragment is shown in Fig. 20.

The next application is analysis of the surface of shot fired from the gun, which is used for gun identification [156]. In this branch the American National Institute of Standards and Technology (NIST) has the lead e.g. It leads a program of model gun cartridge production, where it is fired from each gun directly after manufacturing and on which each gun leaves individual marks [157]. This cartridge is used for the identification of guns, because the marks of the gun barrel are impressed on its surface. The marks are measured as the roughness of each gun which is as adequate as identification as finger prints are for people [158]. Marks from the same gun for two different shots are shown in Fig. 21. Both profiles are compatible with each other, so we can assume that the shots were fired from the same gun. Saving this profile in the database allows fast identification in future. For correct estimation of the profiles of the identified shots the influence of the filtration of the waviness on their description are included in ISO standards. It was concluded that an optimum parameter set was not found yet. The problems and sampling and filtering of multi-process structures, especially atomic force microscopy (AFM) are the best techniques to measure very smooth surfaces.

There are still problems in surface topography characterization. Support is expressed for current standard proposals for a consolidated 3D parameters set. Multi-process textures are becoming very important from the tribological point of view. Various methods of their description are included in ISO standards. It was concluded that an optimum parameter set was not found yet. The problems of sampling and filtering of multi-process structures, especially those having wide valleys are not solved yet. Structured surfaces are becoming both technologically and economically critical. They should be described by special parameters, where a segmentation method can be helpful.

The effects of surface texturing on improving tribological properties of sliding assemblies are very important. The oil pockets can serve either as a micro-hydrodynamic bearing in cases of full or mixed lubrication, a micro-reservoir for lubricant in cases of starved lubrication conditions or a micro-trap for wear debris in either lubricated or dry sliding.

Other effects of surface topography are mentioned in this paper. Examples are only a selection of applications of the analysis of the surface topography, which gains bigger and bigger popularity both in mechanical engineering as well as in other branches which are not connected with traditional engineering experience. Its increasing availability and commonality favors searching further areas of application and possibilities of interdisciplinary researches, often very attractive for workers from distant branches of science.

5. Summary

It seems likely that stylus methods of surface topography measurement will be replaced by optical methods which make it possible to measure surface stereometry in a short time. White light interferometry and confocal microscopes are the most promising techniques. However because of known susceptibility to measurement errors the stylus technique will be in future treated as a reference technique. The ideal solution is a combination of tactile and optical methods. Scanning probe microscopes and among them especially atomic force microscopy (AFM) are the best techniques to measure very smooth surfaces.

There are still problems in surface topography characterization. Support is expressed for current standard proposals for a consolidated 3D parameters set. Multi-process textures are becoming very important from the tribological point of view. Various methods of their description are included in ISO standards. It was concluded that an optimum parameter set was not found yet. The problems of sampling and filtering of multi-process structures, especially those having wide valleys are not solved yet. Structured surfaces are becoming both technologically and economically critical. They should be described by special parameters, where a segmentation method can be helpful.

The effects of surface texturing on improving tribological properties of sliding assemblies are very important. The oil pockets can serve either as a micro-hydrodynamic bearing in cases of full or mixed lubrication, a micro-reservoir for lubricant in cases of starved lubrication conditions or a micro-trap for wear debris in either lubricated or dry sliding.

References
