Quality Evaluation of Surface Layer in Highly Accurate Manufacturing

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Precise characterization of surface topography is very important in many engineering industries. This paper describes potential possibilities of using optical 3D (three dimensional) measurement methods in surface metrology. Surface integrity describes the status and attributes of the machined surface. This paper presents possibilities of using and measurements of surface integrity, namely the surface topography and the physical parameters of which are analysis of microstructure and microhardness of the surface layer.

Key words: machining, optical microscopy, surface morphology, topography

1 Introduction

The accuracy of finished parts after machining is defined as the elimination of dimensional deviations , the deviation of surface roughness, geometric shape and position. Geometrical accuracy obtained after finishing machining is usually the most important from the point of view of functional properties of components used in all areas of industry. The most important factor affecting the geometric accuracy is the accuracy of the machine tool, cutting tool and machining parameters [1]. The quality of machining should not affect the type of fixing and clamping, provided that the clamping force will not cause deformation of the elements. According to Smith [2] mechanisms occurring during machining are so complicated that you cannot state clearly whether a workpiece to be cut "good" or "bad".

According to Mahovic Poljacek et al. [3], a precise characterization of surface topography is of prime importance in many engineering industries. According to Klocke et al. [4], surface quality is of major importance for the in-use component. To ensure better surface integrity and surface quality, special attention must be paid to when choosing cutting parameters [5, 6], tool material and geometry [7] and wedges coatings [8].

2 Trends in Measurement Technology

The last half century of geometrical aspects of surfaces metrology was extremely rich in events related to equipment's 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 [9].

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 [10] 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 – magneticically 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 [9].

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. However 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 [11] (see Fig. 1).

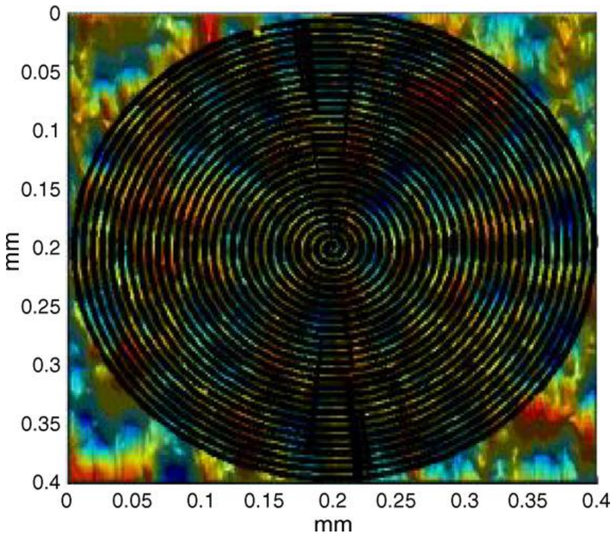


Fig. 1 *Application of spiral sampling [11]*

The last ten years of surface metrology was rich for purchasing devices allowing precisely define the quality of the surface. 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 3D measurement of technical surfaces is a crucial part in checking and controlling the properties and the function of materials or engineering parts. Traditionally 3D measurements have been performed merely by tactile devices but new devices use optical system with vertical scanning. Therefore the optical methods have been described in-depth in the scientific literature, e. g. in Bennett's [12, 13] Tiziani's [14], Leonhardt's [15] 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.

The specimen is placed onto the motorized stage and is illuminated with modulated white light. The coaxial white light is provided by a light source delivered through a beam splitter to a series of selectable, infinity-corrected objectives contained in a six-place nosepiece. The specimen's reflected light is projected through the beam splitter onto a color digital sensor. Optical measurement devices have become increasingly popular in view of their ability to perform area based measurements which are a prerequisite for many powerful surface texture parameters. Undoubted advantage of optical devices is that they operate in a non-contact way and therefore do not damage the surface. In the field of optical surface metrology many technologies have become increasingly popular recently. Among them are methods based on white light interferometry, phase shifting interferometry, structured light techniques, chromatic probe microscopy, confocal laser scanning microscopy CLSM, scanning electron microscopy SEM and atomic force microscopy AFM.

Some important of these new methods are presented below [16]. The principle of operation of each described technique is briefly detailed within the following sub-sections and Table 1 provides an overview of the relevant details for the systems. The figures provided in Table 1 are all quoted from manufacturers' technical specifications and therefore, do not show consistent accuracies due to the necessary grouping of systems within the scientific principles [16].

Vertical Scanning Interferometer

A beam of white light from the source initially passes through a neutral density filter preserving the short coherence length of the white light. A beam splitter then separates the beam into two parts; directing one part towards the sample via an objective lens and interferometer, and the other onto a reference mirror. Recombination of the two reflected beams forms a high contrast pattern of interference fringes when the waves are in phase i.e. when the sample surface is in focus. The fringes appear as bands of light and dark that connect points of equal height. Their number and spacing is determined by the relative tilt between the sample and surface mirror. Due to the short coherence of the filtered light source, only shallow depths of field are in focus, hence the sensor head must scan over a vertical height range. This generates a series of interference patterns, which are captured by a charge-coupled device (CCD) camera to produce interferograms. The interferograms are then analysed by a computer program to determine the surface height at each pixel through the measurement of fringe coherence. The software can then output various graphical representations of the surface including a topographic 3D model. The principle of vertical scanning is presented in Fig. 2. Unfortunately, the resolution of VSI is in the nanometers range, not in fractions of nanometers.

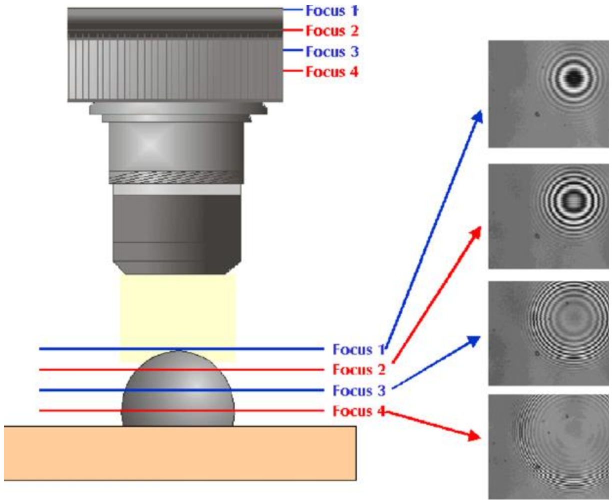


Fig. 2 *Principle of a vertical scanning interferometry [17]*

Point Laser Profilometers

These sensors typically use a triangulation or confocal method to acquire displacement measurement data on a CCD. Two of the systems evaluated use the triangulation method and the other two employ the confocal method. The latter method is a more recently developed system and has the advantage of tolerating changes in surface colour without calibration [18]. The triangulation method focuses the laser beam onto the surface of the sample using a lens. The relative position and intensity of the resultant beam spot is detected by a CCD in the sensor head. This information is used measure the topography of the sample by computing the coordinate position of the beam spot as it traverses or scans the sample. The laser within the confocal sensor head is focused upon the sample by a vibrating objective lens. When the sample surface is in focus, the reflected beam converges through a pinhole and strikes the CCD. The position of the objective lens enables the height (in the z-axis) to be determined; out of focus light does not enter the pinhole or reach the CCD. Only one of the systems enabled a choice in the magnification of the objective lens, which utilised through-the-lens (TTL) focusing.

Confocal Microscopes

This technique employs a similar principle to that of the confocal point laser profilometers in that it combines the ability of the optical microscope to use inter-changeable objective lenses to achieve greater magnification and surface resolution. Of the two systems tested, one used a laser light source while the other used white light. The white light system also employed a multi-pinhole principle, rather than a single pinhole, on a rotating disk within the microscope. This spinning or Nipkow disk has pinholes arranged in a spiral shape. The multiple pinholes enables the microscope to effect a scanning multiple light source to expand the analysis area to that of the objective lens field of view.

Focus-Variation Microscope

This microscope uses an operating principle that combines the small depth of field of an optical system with vertical scanning function to collate images and depth information over a large depth of field. Images with almost 1000 times greater depth of field can be imaged in comparison to a conventional light microscope. The light source is modulated white light that travels to the sample surface via a beam splitter and an infinity-corrected objective. The reflected light is then projected back through the beam splitter onto a colour CCD. At each vertical scanning height an image is captured and for each position on the object sharpness is calculated. It is the variation in sharpness that is used to extract the depth information and generate a 3D model of the surface.

Tab. 1 Chosen optical 3D measurement systems [16]

	Vertical Scanning Interferometer	**Point Laser Profilometers**	**Confocal Microscopes**	**Focus – Variation Microscope**
Light Source	**White light**	**Laser**	**Laser or White light**	**White light**
Objective Lens Magnification	**1x to 50x**	**Typically N/A (TTL 0.5x to 2.0x)**	**10x to 100x**	**10x to 100x**
Working Distance	**7.4 (at 10x)**	**4 to 38**	**10.1 to 0.3**	**23.5 to 3.5**

(mm)				
Resolution (µm) Vertical	0.03	0.01 to 0.05	0.01 to 0.001	0.1 to 0.01
Resolution (µm) Lateral	Not stated	1 to 30	3.1 to 0.12	1.1 to 0.4
Max. Surface Angle (°)	13.1 (higher for non-spectacular surfaces)	70	70 (85 in future)	90

3 Examples of applications

This paper focuses on measurement techniques and their possibilities of using in surface metrology in Research and Production. All examples presented in this paper were performed using Infinite Focus Measurement Machine (IFM) showed on Fig. 3. IFM is an optical 3D measurement device which allows the acquisition of datasets at a high depth of focus. IFM used to measure Focus-Variation method. This method uses an operating principle that combines the small depth of field of an optical system with vertical scanning function. Images made by IFM has 1000 times greater depth of field in comparison to a conventional light microscope. The light source is white light that travels to the sample surface via a beam splitter and an infinity-corrected objective.

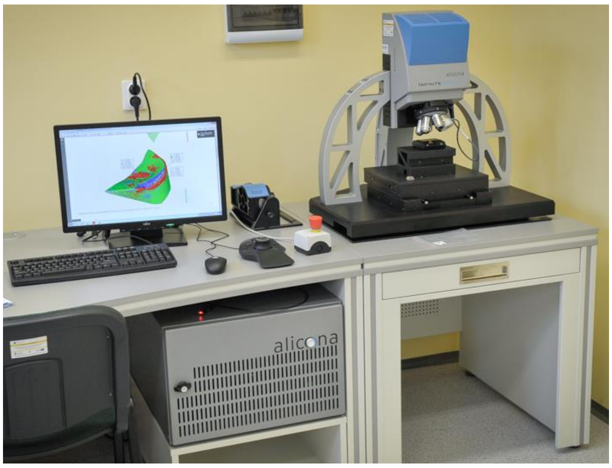
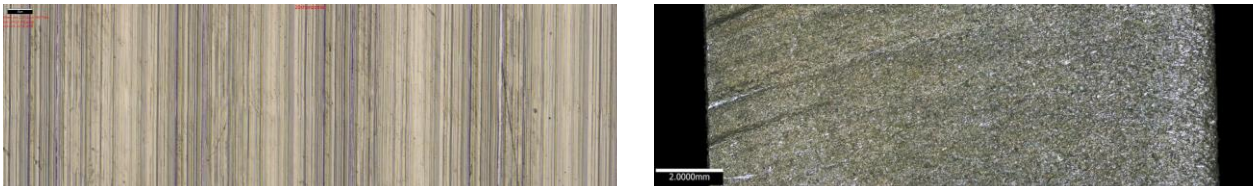


Fig. 3 *Infinite Focus Measurement Machine*

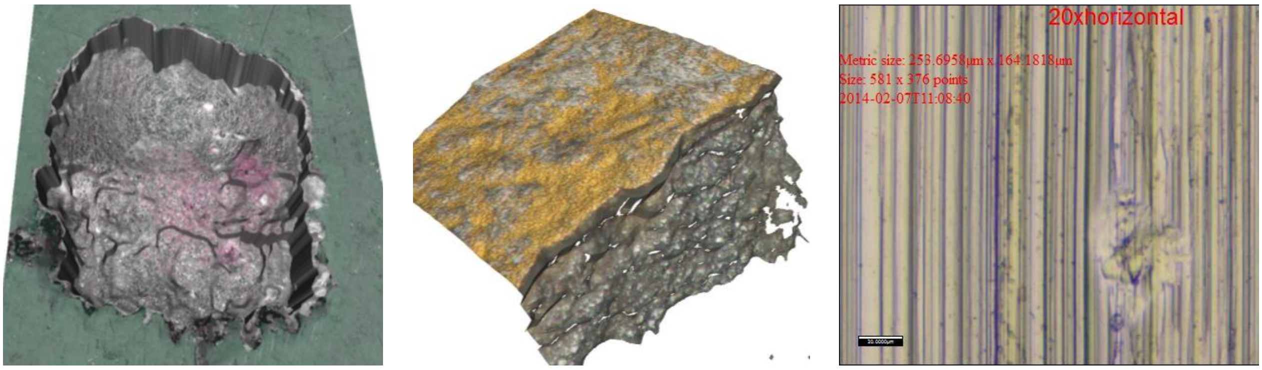
Optical 3D measurement systems are successfully used as tool measurement devices for cutting wedge measurement, as roughness measurement devices and as form measurement devices in high resolution. The surface topography is commonly used to analyze surfaces after different types of machining – typical/conventional (turning) [19, 20] and unconventional (abrasive water jet machining) [21-25]. Fig. 4 shows a surface after conventional and unconventional cutting.



a) **b)**

Fig. 4 *Surface morphology: a) after turning, b) after abrasive water jet machining*

Topographic analysis of the surface is also used in Failure Analysis. With use of this method the surface of a machine parts is tested at different stages of failure (Fig. 5 - corrosion analysis, fracture science, surface damage).



a) **b)** **c)**

Fig. 5 *Surface morphology of a) corrosion analysis, b) fracture, c) surface damage*

Using a 3D Optical measurement method one can perform measurements of material properties such as surface hardness. Hardness measurements on the micro scale, we are able to read measuring cavity made by the diamond indenter. This measurement method enables the visualization of the measured shape and because of the possibility of high magnification - precise quantitative assessment of even two-phase structures also. Figure 6 shows the trace of the indenter on the surface of a two-phase ferritic - austenitic duplex steel. Furthermore, the optical analysis allows the precise measurement of the bottom of indentations due to possible rotation of the virtual sample.

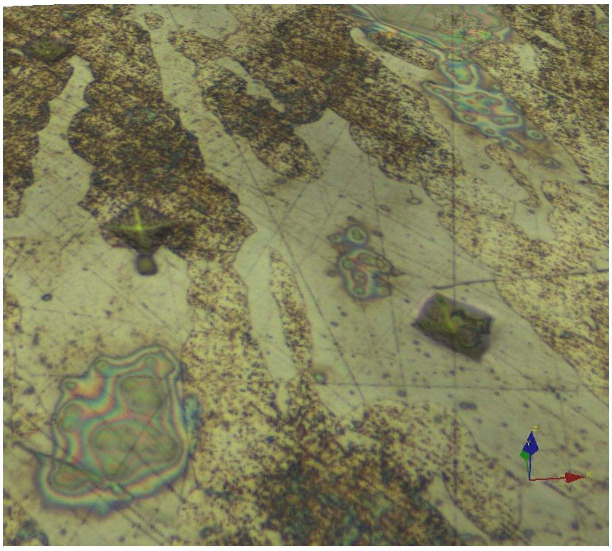


Fig. 6 *Trace the indenter on the surface of duplex steel (dark: ferrite, bright: austenite)*

Probably the most common form of use of a 3D Optical measurement method is the possibility of its to use in quantitative analysis of the surface quality, such as the profile roughness analysis (Figure 7) and load capacity curves - Abbott - Firestone curves) (Fig. 8) depending on the various machining conditions.

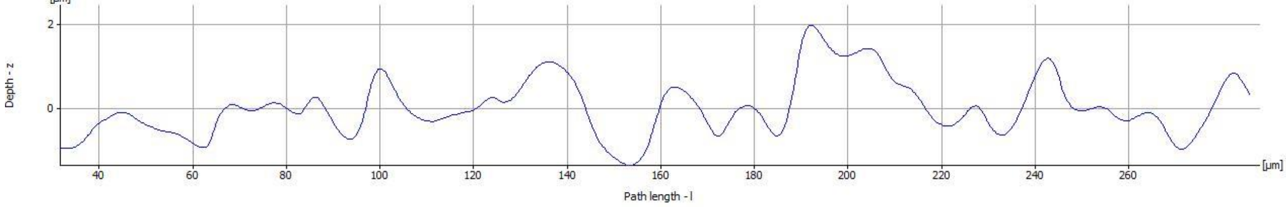


Fig. 7 *Surface roughness profile for Ra parameters- Lc 800 μm*

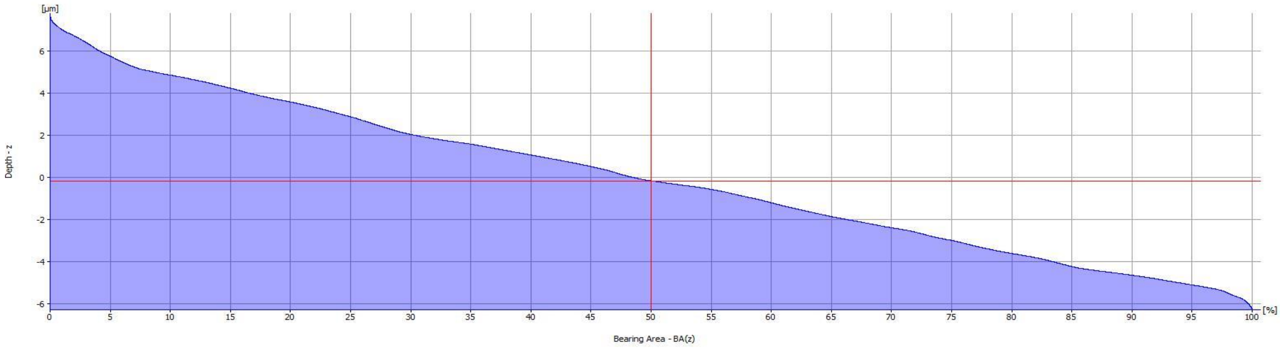


Fig. 8 *Load capacity curve (Firestone-Abbott Curve for Roughness Profile)*

Another very often represented in scientific publications [26-29] form of using optical 3D measurement method is analyzing the wear of cutting wedges. Thanks to the possibilities offered by optical measurement there is possible to analyze problems related to the tool wear mechanism (Fig. 9).

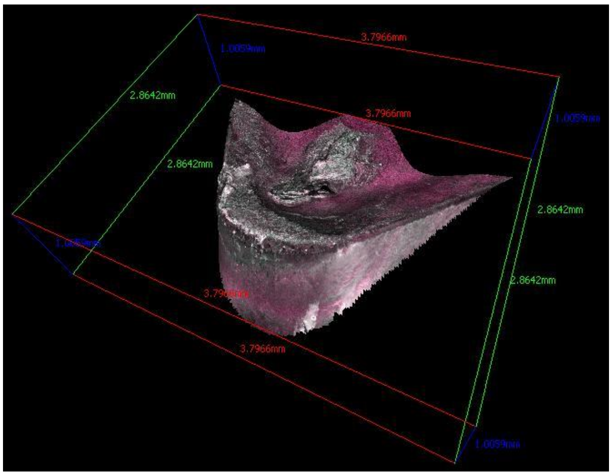


Fig. 9 *Topography of the tool point wear*

4 Conclusions

The paper presents selected possibilities of using optical measurement methods for the analysis of surface topography. Analysis of surface topography is gaining popularity both in research and in the design and control in the practice of manufacturing companies. Increasing the competitiveness of companies in the global market and the availability of high-tech measuring devices promotes the pursuit of further areas of application in industry and research opportunities. Optical 3D measurement methods of surface topography replace traditional methods of measurement of touch with the stylus. Among other things, this is due to the fact that the optical methods capable of performing much faster measurements and minimize the limitations associated with the shape of the surface.

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