

NON-CONTACT OPTICAL METROLOGY FOR AUTOMATED IN-PROCESS INSPECTION OF MACHINED SURFACES

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Abstract: This work presents a concise review of selected issues related to non-contact optical metrology in applications where automated in-process inspection is involved. A brief description of the in-process inspection and applicable procedures were presented. A laser method based on analysis of scattered light was elaborated in greater detail. In addition to the above, a short review of selected technical solutions in a form of an experimental and commercially manufactured measurement systems was presented. This review concentrates on describing of the most important metrological parameters, principles of operation and areas of applications of the aforementioned measurement systems. In the final part of the work a subjective selection of literature references was listed.

Keywords: Optical metrology, laser scatterometry, in-process inspection, machined surfaces, surface texture

1. INTRODUCTION

Modern manufacturing industry (especially machine, automotive and aerospace sectors) requires reliable solutions that integrate measurement procedures and modern machining technologies [1]. This need arise from the necessity of producing high-quality components that suffice a number of functional and operational criteria while satisfying the ever-increasing demands of the modern customers. Meeting these requirements by the currently produced machine parts imposes on manufacturers the necessity of using of a wide range of procedures related to the quality assurance. It does not only refers to proper geometrical dimensions, but also to appropriate state of surface texture. The specificity of the industrial conditions makes, that the above mentioned procedures in many cases need to be automated and used in the framework of the in-process inspection [2]. In many cases, such an inspection is carried out by various types of optical measurement systems. The most important in this context are those, which use laser radiation in the range of visible spectrum and near IR. The introduction of high manufacturing standards, due to e.g. implementation of automated non-contact in-process inspection systems, contributes to the improvement of quality of modern industrial production.

Generally, in-process inspection of a surface is used to check its quality [3,4]. This inspection is performed during production process to detect errors and imperfections of the surface. The purpose of the in-process inspection is to additionally pinpoint problems with the surface texture that need correction and also to identify errors earlier in the process. The benefits of in-process inspection include, among others:

- reducing the number of defects,
- possibility of achieving high quality and repeatability of manufactured components,
- reduction of time required to produce the single component.

2. CHARACTERISTICS OF THE OPTICAL METHODS USED IN THE IN-PROCESS INSPECTION

In work [5], K. Vacharanukul and S. Mekid (University of Manchester) characterized the main techniques for in-process dimensional inspection. Similar methods can be used to control the surface. M. Shiraiishi (Ibaraki University) presented a succinct review of these methods in the fundamental works in this field [6,7]. The most commonly methods used are as follows: mechanical, optical, electrical, pneumatic and ultrasound. Also T. R. Thomas (Halmstad University), in [8] has examined methods that can be applied to in-process inspection of surface texture. The basic criterion for the choice of the method was linear speed at which the tested surface moves. In [9] it was found that mechanical methods are suitable for in-process inspection if the surface moves at a low speed. Big expectations for a practical solution to the problem of surface inspection are put on application of optical methods. The classification of the most important methods used for automated in-process inspection of machined surfaces is shown in Tab. 1.

Table 1: Classification of methods for automated in-process inspection of machined surfaces

Group of methods	Method	Principle
Mechanical	Stylus profilometry	Physically contact between stylus and surface of measured object
	Confocal method	Analysis focusing of the light on the surface during scanning process
	Interferometry	Analysis of fringe image characterize the surface of measured object
Optical	Scatterometry	Analysis of light scattered from off the surface
	Triangulation	Analysis of light reflected from off the surface with angular detection
	Structured light	Analysis of pattern defects, which is projected onto measured surface
Pneumatic	-	Analysis of the air gap between the measurement nozzle and surface
Electric	-	Analysis of the capacitor with 2 electrodes (sensor and surface)
	-	Analysis of the electric field properties (e.g. change of reluctance)
Ultrasound	-	Analysis of the ultrasound wave reflected from off the surface

Table 2: Characteristics of the optical method used for automated in-process inspection of machined surfaces

Group of optical methods	Method	Assessed parameters	Measuring range, μm	Selected examples of applications
Triangulation	Laser triangulation	l, h ¹⁾	10–10000	Inspection of dimensions, distances and displacements in micro and macro scale
	Structured light	l, h, z ¹⁾	1–10000 ²⁾	Inspection of dimensions and (alternatively) shapes of the surface in micro and macro scale
Light scattering	Laser scatterometry	Rq	0.0001–0.01 ³⁾ 0.002–0.2 ⁴⁾	Mostly for quality inspection of the surface microirregularities (e.g. optical elements, silicon wafers)
		Rq, Ra	0.01–1 ⁵⁾	In-process inspection of machine parts in industrial conditions (e.g. surface of crankshafts)

l – length or distance, *h* – height, *z* – height in a 3-dimensional system, *Ra* – arithmetic mean deviation of the assessed profile, *Rq* – root mean square deviation of the assessed profile, ¹⁾ 2D-3D parameters depending on the used method, ²⁾ Depending on resolution of the optical system, ³⁾ Measuring range of the σ parameter for visible light wavelength $\lambda = 0.632 \mu\text{m}$, ⁴⁾ Measuring range of the σ parameter for IR light wavelength $\lambda = 10.6 \mu\text{m}$, ⁵⁾ Typical measuring range for commercial in-process measurement systems. The range can be extended to max. *Ra* = 10 μm .

D. Yougeng (Xi'an Polytechnic University) in [10] presented an overview of optical methods for in-process inspection of surface roughness. The techniques based on lasers form an important part of an optical approach. Among of those are the following:

- laser scatterometry, based on the phenomenon of light scattering,
- laser triangulation,
- methods using projection and analysis of the optical structured light patterns.

The basic properties of these methods are listed in Table 2.

3. CONCISE REVIEW OF MEASUREMENT SYSTEM FOR IN-PROCESS INSPECTION

Analyzing the possibility of using a measurement system for in-process inspection, needs consideration of conditions under which such an inspection will be carried out. The main features, which should characterize an automated in-process inspection system are e.g.:

- measuring range (generally small, the range of parameters of surface texture that can be achieved during the machining),
- sensitivity of the system (high and adapted to the type of treatment so that any significant changes to machined surface can be evaluated using this system),
- measurement uncertainty (as small as possible, usually ranges from 10-20% of the measured value),
- measurement time (as short as possible, thereby enabling greater number of measurements to be made in a given time unit). Depending on type of the system and its purpose, measurement times can range from hundredths of a second to several seconds. However, sometimes excessive reducing of the measurement time may decrease the measurement accuracy.

Achieving satisfactory level of the parameters mentioned above is not easy in practice. Majority of the existing systems for in-process inspection of the surface texture is experimental. Only a few of them are manufactured commercially.

Among the experimental systems used for research, an interesting system was developed [11] by researchers at the National University of Singapore. The integrated probe is designed to evaluate the surface roughness by the light scattering method, known as ARS (*Angle Resolved Scattering*), and micro-displacements using laser

triangulation. The research found that the probe can evaluate the surface roughness (*Ra* parameter) ranging from 0.005 μm to 0.1 μm . However, it is possible to measure of the displacement in range $\pm 300 \mu\text{m}$.

The above mentioned probe has several modifications. One of them is presented in [12]. The instrument has a relatively simple construction. It uses a semiconductor laser with a wavelength $\lambda = 780 \text{ nm}$ and a linear CCD detector, allowing the recording of the scattered light for the scattering angles to $\varphi = 28^\circ$. The special design of the probe was adapted for use in industrial environments. It was characterized by a low sensitivity to movements and vibrations of the measured elements. The instrument can be used for in-process inspection of the surface roughness of the machined (turned, polished and lapped) parts. Experimental studies have confirmed the possibility of an effective assessment of surface roughness (*Ra* parameter) in a much wider range of between 0.005 μm to 6 μm . G. Y. Tian (University of Huddersfield) and R.-S. Lu (Hefei University of Technology) used a similar approach in [13]. It has been implemented in an optical measuring head of similar design as described in [12].

Creation of a commercial system Lasercheck[®] is related to the research carried out by J. G. Valliant, M. P. Foley (Optical Dimension LLC) and J. M. Bennett, which elaborates the use of optical methods for the rapid in-process inspection of the surface roughness in industrial conditions [14]. On this basis, Optical Dimension LLC (corporation Schmitt Industries, Inc.) started production of Lasercheck[®] heads (Figure 1b). The heads were produced in two versions: portable and stationary. The stationary head allows the inspection of the surface roughness with a frequency of 10 times per second. The laser beam with wavelength $\lambda = 660 \text{ nm}$ is incident on the test surface at angle of 75° . The scattered light is measured in two ways: linear CCD detector and two separate photo detectors. The measuring range of surface roughness (*Ra* parameter) was maintained in the range from 0.05 μm to 0.5 μm , and could be expanded to 1 μm . In new Lasercheck[®] heads only the linear CCD detector is used. The measuring range of new heads is wider; from 0.03 μm to 2 μm (portable version 6212B and 8826B) and from 0.01 μm to 2 μm (stationary version 6212POM and 8826POM). Optical Lasercheck[®] heads are used in automotive industry. Their primary application is to control quality of manufactured engine and steering, camshaft, crankshaft, drive shafts and suspension components.

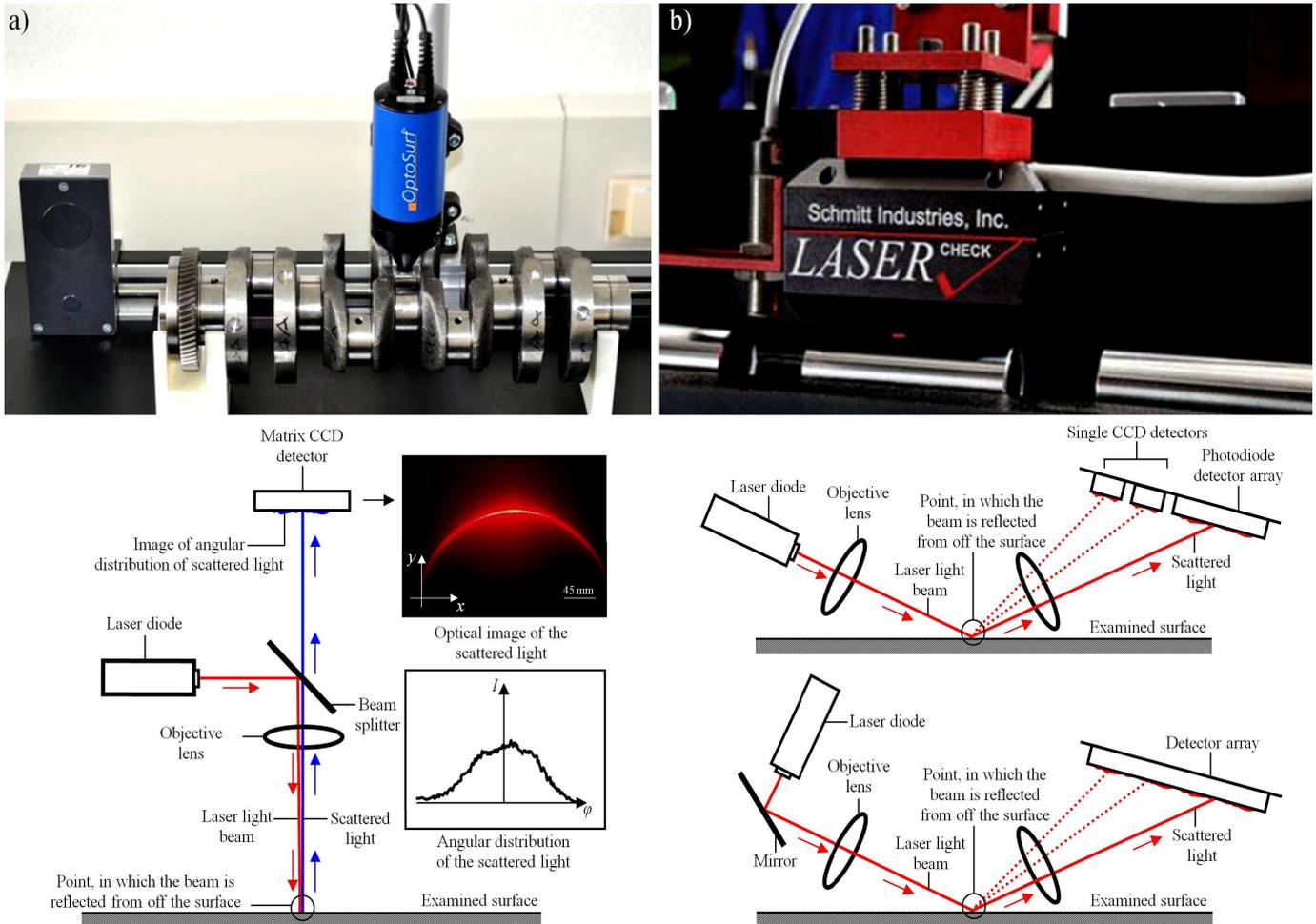


Fig. 1: The commercially available measurement systems used for automated in-process inspection of machined surfaces: a) OS 500 by OptoSurf (general view of the system (top left) and diagram showing principle of surface roughness measurement (bottom left)), b) Lasercheck[®] by Schmitt Industries, Inc. (general view of the model 6212POM (top right) and measuring principle used in the older and current production variant of the system (bottom right))

Another system - OS 500 is manufactured by German OptoSurf (Figure 1a). It is the result of over 20 years of research and implementation projects conducted by the team of R. Brodmann, O. Gersthofer (Werke G. Rodenstock), G. Thurn (Technical University of Berlin) and others. These studies led to the development of in-process methods using the phenomenon of light scattering. This allowed the Werke G. Rodenstock to begin, in 1984, commercial production of RM 400 and RM 500 systems [15]. The RM 400 system was used to assess the surface roughness. It allowed measurements of R_a parameter in range between $0.005 \mu\text{m}$ and $2 \mu\text{m}$. The automotive industry has applied the above systems for inspection of automotive parts (such as pistons, valves, gears, crankshafts). These systems have been implemented by such car manufacturers as Volkswagen and Daimler. The design of OS 500 benefits from the experience gained during operation of the both predecessors.

Similarly to the previous units, OS 500 system uses the ARS method to evaluate roughness of the surface. New optical and electronic elements with increased sensitivity were integrated into the system to allow obtaining results of the measurements with relatively high accuracy. The large number of measurements (about 2000 per second) performed in the

course of the evaluation also contributes to the better accuracy. The system enables in-process inspection of the surface roughness (R_a parameter) in range between $0.05 \mu\text{m}$ and $3 \mu\text{m}$ (measurements in cross section) and from $3 \mu\text{m}$ to $30 \mu\text{m}$ (measurements in longitudinal section).

Automated systems for in-process inspections are constantly upgraded and modified to adapt them to the specific measurement tasks. Nevertheless, new designs and measurement solutions are being introduced. Application of hybrid systems is a new trend in implementation of in-process inspection systems. The hybrid system comprises several measurement techniques within a single device. Usually, this system uses common optical components (lenses, light sources, etc.) for different techniques and allows to perform advanced multi-parametric evaluation of a tested surface. At the Koszalin University of Technology for many years research on integration of laser methods and construction of experimental setups had been carried out [16].

Figure 2 presents the new laser measuring system. It integrates the following laser methods:

- ARS modified method (to assess the surface roughness),

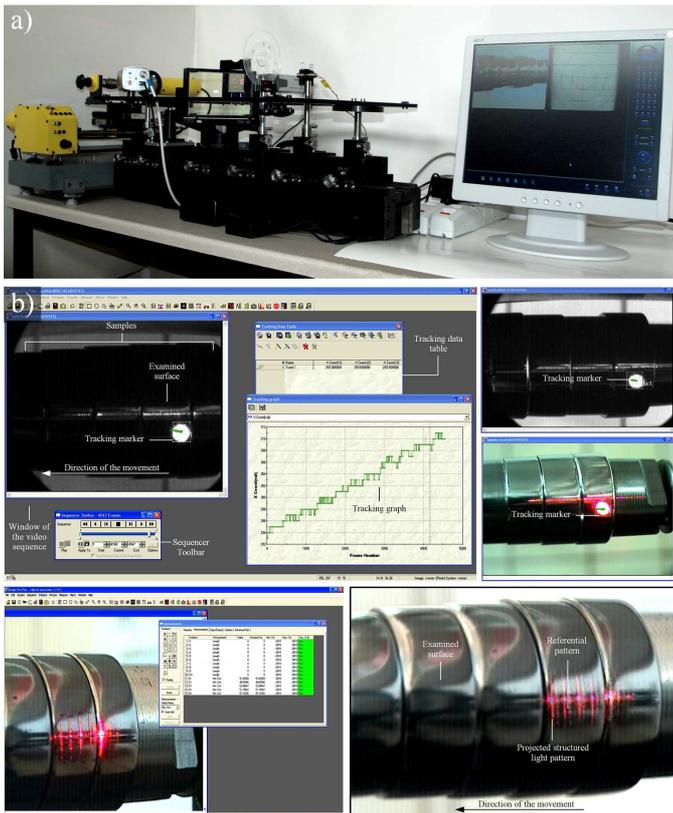


Fig. 2: Experimental measurement system for the in-process inspection of machined surfaces designed and developed in the Koszalin University of Technology: a) general view of the system, b) exemplary windows of Image Pro[®]-Plus software used for processing of measurement data

- laser triangulation method (to assess the dimension)
- method using projection of structured light patterns (to assess the shape of the surface).

The above methods are supported by techniques of image processing and analysis, including the image tracking and image stacking [17]. Integration of several methods allows evaluation (simultaneous or sequential) of the parameters characterizing the test object. Analysis of the measurement data is performed in Image-Pro[®] Plus environment by Media Cybernetics, Inc. (USA). Screenshots showing the software used during surface size and shape evaluation are presented in Figure 2b. Intensive testing led to determining the basic metrological parameters of the developed system. Surface roughness measuring range (for R_a parameter) is between 0.02 μm and 1 μm .

5. CONCLUSIONS

Optical metrology of surface is a rapidly growing field of modern science and technics. This has been proven by the numerous applications, mainly in an automated control of manufacturing processes using in-process inspection systems.

A brief overview of methods and measuring equipment used in in-process inspection of machined surfaces indicates that the most commonly used for this purpose are methods of laser scatterometry, laser triangulation and structured light.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the financial support of this work from The National Science Center of Poland.

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