UDC 621.9.08:681.5.08
DOI https://doi.org/10.32782/2663-5941/2024.1.1/37

Melnychuk B.P.
National Technical University of Ukraine
"Igor Sikorsky Kyiv Polytechnic Institute"

Shevchenko V.V.
National Technical University of Ukraine
"Igor Sikorsky Kyiv Polytechnic Institute"

AUTOMATED SYSTEM FOR CONTROLLING THE SURFACE ROUGHNESS PARAMETERS OF PARTS

The article presents an automated system for monitoring the surface roughness parameters of parts using the optical method of confocal chromatic sensing with on-site measurements.

One of the most important parameters of parts is reliability and accuracy. These parameters directly depend on the surface roughness parameters, so it is important to process parts with the specified parameters that will meet the purpose of the part. There are many methods for measuring roughness parameters, most of which involve removing the part from the machine between operations, which introduces some of the errors associated with part installation into the machining process. In addition, conventional methods and portable devices for measuring roughness parameters are often impossible to use for measuring parts of small dimensions and complex geometric shapes.

The method of chromatic confocal sensing, which is based on the use of the phenomenon of light dispersion, i.e., reflects the dependence of the refractive index on the medium or frequency of light, is used in this work. The optical system is based on the design of a confocal chromatic microscope. The ray tracing method was used to determine the focal lengths for different light wavelengths passing through the objective. After passing through the lens, white light is decomposed into a spectrum, with each wavelength focused at a certain distance from the lens to form a set of monochromatic images. The Lagrange multiplier method was used to develop and visually interpret the mathematical relationship between focal length and light wavelength. Thus, using the method of confocal chromatic sensing, it is possible to measure the surface geometry and calculate the roughness parameters based on the measurements. The paper also presents and describes a block diagram of the algorithm for controlling the roughness parameters, a block diagram of the algorithm for measuring the roughness parameters, and a block diagram of an automated system for controlling the roughness parameters of the surface of parts.

An automated system for controlling the surface roughness parameters of parts by the optical method, with on-site measurements, will increase the measurement accuracy and production productivity.

Key words: *CNC machines, automated production, surface roughness parameters, in-situ measurements, chromatic confocal sensing method.*

Introduction. Roughness refers to the microgeometry of a solid and determines the nature of the interaction between a device part and other parts in the machine tool system. This is an important indicator in the product specification, determined by the degree of deviation of the actual surface profile at the base length from the theoretical smooth surfaces of a given geometric shape. Roughness determines the wear resistance and strength of a part, the tightness of joints, chemical resistance, and the appearance of the part. Depending on the conditions, the appropriate roughness parameter is assigned. For example, for friction parts, this parameter should be minimal, as high roughness will accelerate wear in the contact areas. At the same time, surfaces that do not have contact with other surfaces or do not perform any functions may have a high roughness parameter, since additional processing is unnecessary [1].

According to research, surface roughness measurements can be divided into two types: contact (profilometers and profilographs) and non-contact (optical, pneumatic, ultrasonic, electrical, and temperature). Optical methods are most often used because they provide high measurement speed and high resolution. Measurements can be carried out with preliminary removal of the part and its installation in the measuring device, but such methods are undesirable because they increase equipment downtime and therefore reduce production efficiency, while at the same time introducing errors in the installation of the part during subsequent processing. Therefore, in-situ measurement methods are increasingly used, i.e., measurements do not require part removal and are performed directly in the machine tool holder [1].

Formulation of the problem. To measure the roughness parameters using traditional methods, it is often necessary to remove the part from the machine between operations, which can cause some errors and inaccuracies in the part processing process. At the same time, portable devices for measuring roughness parameters are unsuitable for measuring parts of small dimensions and complex geometry.

The purpose of the article. The aim is to develop an automated system for monitoring the surface roughness parameters of parts using the optical method of confocal chromatic sensing, with measurements carried out on site. The advantages of such a system will be that measurements will be carried out on-site, which will reduce the impact of installation errors on the accuracy of the part as a whole, and the use of the optical method will increase measurement accuracy, reduce production costs, and increase its productivity by reducing the number of defective parts.

Presenting main material. Roughness is a set of irregularities that form a real surface relief that differs from the specified one, with a relatively small step on the base length. It is formed as a result of processing: protrusions and depressions are formed, the surface layer of the material is strengthened or destroyed, and internal stresses occur. Roughness directly depends on the method of machining the part, the cutting modes, the overall stiffness of the machine-tool-part system, the materials of the part itself and the cutting tool, and the heating. The roughness index affects the performance characteristics of machine parts and assemblies – friction, wear resistance, tightness, fatigue life, corrosion resistance, tribological characteristics, heat transfer, adhesion, contact pressure, aerodynamic characteristics, and electrical contact. Therefore, machining parts with specified roughness parameters is very important.

In accordance with DSTU ISO 4287:2012, roughness parameters are determined by six indicators, they are divided into 3 types: height, step and height-step.

The altitude ones include the following: *Ra* is the average arithmetic deviation of the profile within the base length; *Rz* is the sum of the average absolute values of the heights of the 5 largest protrusions and depths of the 5 largest depressions of the profile within the base length; *Rmax* is the distance between the line of profile protrusions and the line of profile depressions within the base length [2];

The following are considered to be step parameters: *S* is the arithmetic mean of the step of profile irregularities along the vertices within the base length; *Sm* is the arithmetic mean of the step of profile irregularities within the base length;

Only one parameter belongs to the height-step parameters: *tp* – the ratio of the reference length of the profile to the base length.

In foreign literature, you can also find many other roughness parameters such as: *Rq* is the root mean square value, or the root mean square value of the deviations of the profile height from the midline; *Rvi* is the maximum depth of depressions below the midline within the reference length; *Rpi* is the maximum height of peaks above the midline within the reference length; *Rsk* is the asymmetry, or the measure of asymmetry of the profile relative to the midline; *Rku* is the kurtosis, or the measure of sharpness (or tailing) of the profile relative to the midline [3].

There are many methods for estimating surface roughness. There are two ways to assess roughness: qualitative and quantitative.

Qualitative assessment is often used in production conditions. For this purpose, the so-called standards are used – specially made surface samples with a pre-measured and specified roughness. The surface roughness is assessed by visual comparison.

Quantitative methods for assessing roughness are performed in two ways: contact and non-contact [4].

Contact methods include those that use special devices such as profilers and profilometers.

There is also a method of casts used to assess roughness in hard-to-reach areas.

Non-contact methods include: temperature, pneumatic, ultrasonic, but such methods allow to determine the roughness only indirectly, so there are a number of optical methods that allow to accurately determine the surface roughness, these include the method of light and shadow intersection, interference, raster, laser scattering, and chromatic confocal sensing, the latter has a number of advantages over other methods, so it was used in the study.

The chromatic confocal sensing method is based on the use of the phenomenon of light dispersion.

The advantages of this method are as follows:

This method can be used to measure any surface: mirror, curved, inclined (up to 82°), rough, transparent, etc;

The measurement by this method does not form shadow zones, which allows you to evaluate not only the roughness parameter, but also the surface topography;

Taking into account the fact that the light wavelength can be divided many times, this method has a very high resolution (up to 1 nm), which depends on the resolution of the spectrometer and the accuracy of the lenses in the optical system;

As long as the measurements are performed within the permissible range, a certain wavelength will always be focused on the surface of the part;

The optical system and the controller can be connected via fiber optics, which allows for remote measurements;

The accuracy of the confocal chromatic sensing method is not affected by external interference, such as changes in temperature, light, or electromagnetic interference;

This method can also be used to measure the thickness of thin transparent films on the surface of parts (up to 6 layers);

This method can also be used to measure the roughness of surfaces inside holes [5];

In addition, this method achieves a high frequency of data acquisition (up to 70 kHz).

To build the optical component of the system for confocal chromatic sensing, we need: a full-spectrum white light source, for which we decided to use LEDs, since they consume little energy and have a long service life, a 50:50 beam splitter, which was used as a translucent mirror, two apertures, and an HPCS300 minispectrometer. The advantages of this spectrometer are the ability to connect both via USB and RS285 protocol, which allows for remote and online measurements [6, 7].

We also used a plan apochromatic microscope objective with a twenty-fold magnification and a numerical aperture of about 0.75 (Fig. 1), made under patent of March 17, 1998, No. 5 729 391, inventor Itoe Ito, Kawasaki, Japan, assignee of Nikon Corporation, Tokyo, Japan [8].

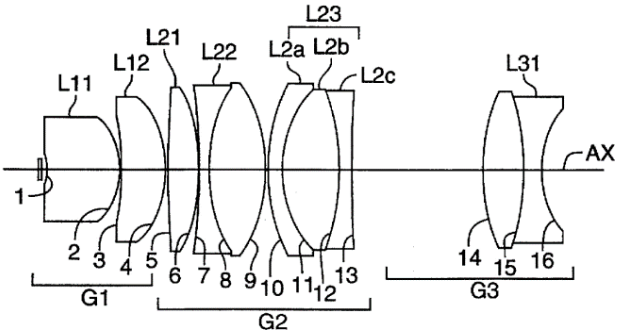

Fig. 1. Plan apochromaticmicroscope objective [8]

Fig. 2 shows the schematic arrangement of the elements of the optical component of the roughness parameters control system.

The principle of operation of the optical component of the roughness control system: the light source 1, which contains a spherical mirror, focuses the light so that it passes through the input aperture 2 with a hole

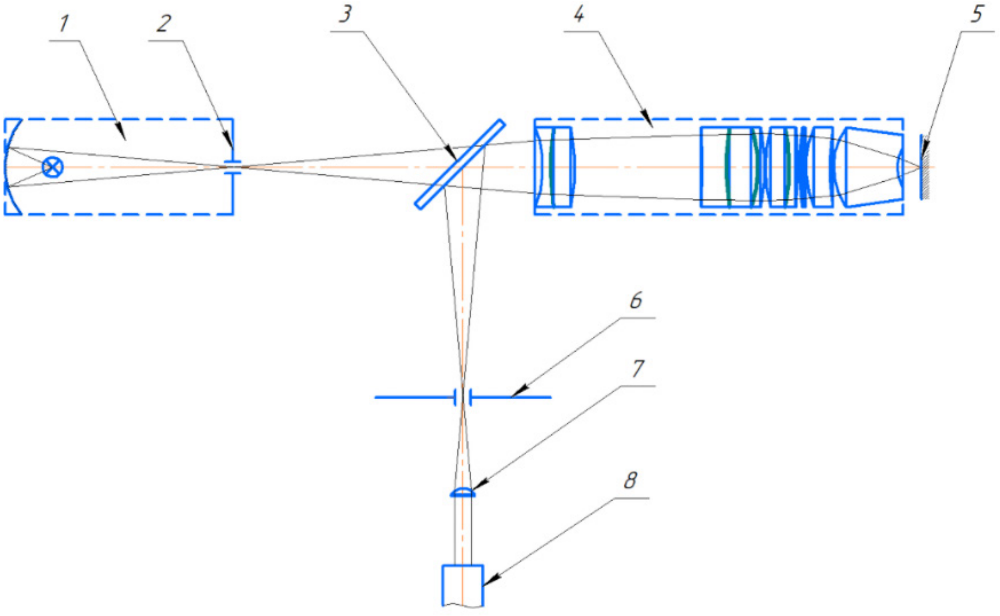

Fig. 2. Schematic arrangement of elements of the optical component of the system for controlling roughness parameters: 1 – light source; 2 – inlet aperture; 3 – beam splitter 50:50; 4 – microscope objective; 5 – surface under study; 6 – outlet aperture; 7 – collimator lens; 8 – spectrometer objective

size of 1 mm. After passing through the aperture 2, the light passes through a translucent mirror, which serves here as a beam splitter 3 50:50 and enters the lens 4, after passing through the lens, the light is decomposed into a spectrum and only one wavelength is focused on the surface under study 5, the focused light is reflected back and after passing through the lens 4 enters the beam splitter 3, from here the reflected part of the light returns back to the source 1, and part enters the direction of the output aperture 6. Its role is to filter out the unfocused wavelengths and let only the focused light pass through. The filtered light enters the collimator lens 7 and then enters the spectrometer objective.

The tracing method was used to calculate the focal lengths for different wavelengths. A collimating lens consists of two surfaces on which light is refracted and a medium in which light passes. Studies [9] have shown that the nature of refraction and transmission of a light beam in different media can be described mathematically.

The refractive matrix describes how a light wave is refracted at the boundary of two media (for example, air-glass), and is written in the form of a matrix $\Re$:

$$\Re_1 = \begin{bmatrix} 1 & -D_1 \\ 0 & 1 \end{bmatrix}, \tag{1}$$

where: D_1 – is the force of one refractive surface, which is calculated as:

$$D_1 = \frac{n_{t1} - n_{i1}}{R_1}, \tag{2}$$

where: n_{t1} – the refractive index in the second medium (or in the medium of beam transmission); n_{i1} – refractive index in the first medium (or medium of incidence); R_1 – surface radius.

The transmittance matrix describes how a light wave behaves in a homogeneous medium, we write it in the form $\Im$:

$$\Im_1 = \begin{bmatrix} 1 & 0 \\ d_{21}/n_{t1} & 1 \end{bmatrix}, \tag{3}$$

where: d_{21} – distance between the point of incidence of the beam on the first surface and the second.

Since the lens consists of two surfaces and a medium, the system matrix A, which describes the nature of the light wave passing through the bulk lens, will consist of two refractive matrices and one transmission matrix, and will have the following form:

$$\mathrm{A}_{21} = \Re_1 \Im_1 \Re_2 = \begin{bmatrix} 1 & -D_1 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ d_{21}/n_{t1} & 1 \end{bmatrix} \begin{bmatrix} 1 & -D_2 \\ 0 & 1 \end{bmatrix} \tag{4}$$

After mathematical transformations, this matrix is written in the following form:

$$\mathrm{A}_{21} = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} = \begin{bmatrix} 1 - \dfrac{D_2 d_l}{n_l} & -D_1 - D_2 + \dfrac{D_2 D_1 d_l}{n_l} \\ \dfrac{d_l}{n_l} & 1 - \dfrac{D_1 d_l}{n_l} \end{bmatrix} \tag{5}$$

where: d_l – lens thickness, mm; n_l – refractive index of the lens.

The determinant of this matrix is always equal to one $|\mathrm{A}_{21}| = 1$. Additional studies have also shown that the matrix term $-a_{12} = -\dfrac{n_{i1}}{f_O} = +\dfrac{n_{t2}}{f_I}$

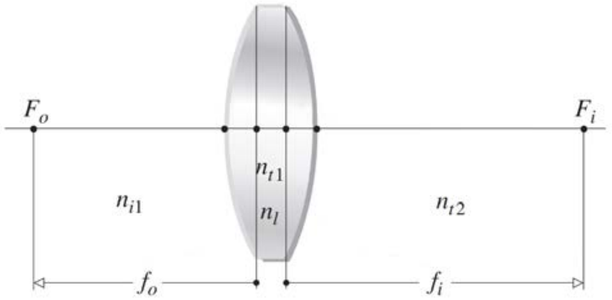

Fig. 3. Focal lengths of lenses

So, to calculate the focal lengths for different wavelengths for a lens, you need to calculate the matrix $\mathrm{A}_{16,1}$

$$\mathrm{A}_{16,1} = \Re_{16}\Im_{1615}\Re_{15}\Im_{1514}\Re_{14}\Im_{1413}\Re_{13}\Im_{1312}\Re_{12}\Im_{1211}\Re_{11} \times$$
$$\times \Im_{1110}\Re_{10}\Im_{109}\Re_{9}\Im_{98}\Re_{8}\Im_{87}\Re_{7}\Im_{76}\Re_{6}\Im_{65}\Re_{5}\Im_{54}\Re_{4}\Im_{43}\Re_{3}\Im_{32}\Re_{2}\Im_{21}\Re_{1}$$

Calculations have shown that different focal lengths of the light wave passing through the lens correspond to different focal lengths:

Table 1

Table of fixed values of the function $f(\lambda_i)$

λ_i, nm	380	435	490	580	700
$f_i(\lambda_i)$, mm	6.648	6.782	6.881	6.993	7.091

Accordingly, by interpolating using the Lagrange multiplier method, we obtain the function of the focal length f_i versus wavelength λ_i (Fig. 4).

$$f_i(\lambda_i) = -4.11\lambda_i^4 + 16.31\lambda_i^3 - 22.26\lambda_i^2 + 13.56\lambda_i + 3.91. \tag{6}$$

Figure 5 shows the algorithm of the roughness control process. The algorithm for measuring the roughness parameters is as follows: first, the user enters the base length or roughness class at the setup stage. After that, the corresponding measurement modes are read from the microcontroller memory. Next, the LED and spectrometer are powered on. Before starting roughness measurements, the sensor will first measure the received spectrum to make sure that it is within the extreme focal lengths. If

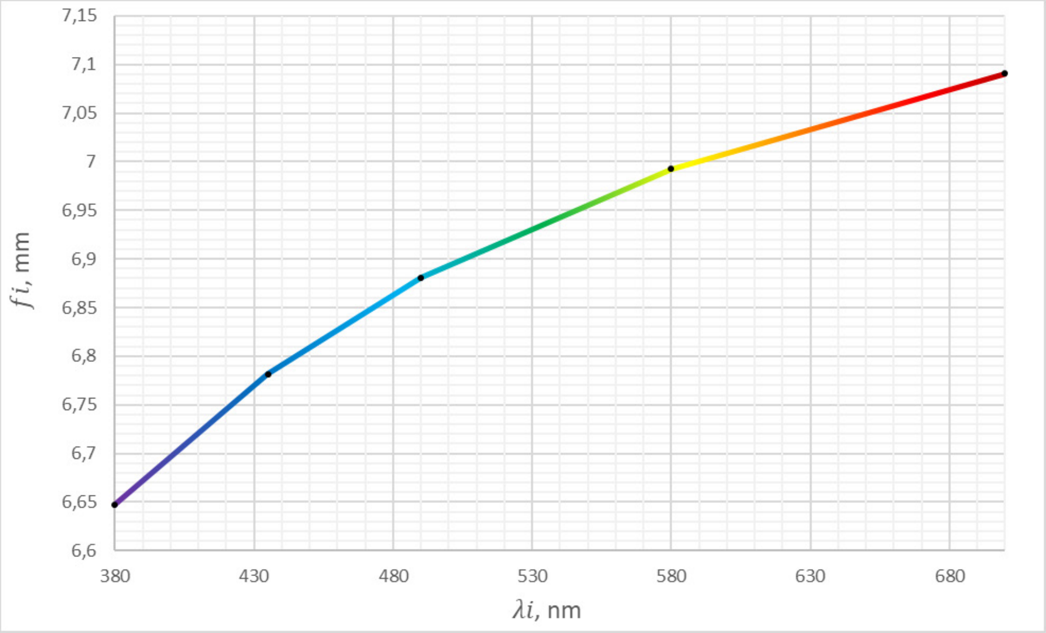

Fig. 4. Dependence of the focal length f_i on the wavelength λ_i

the sensor is too close or too far from the surface of the surface to be examined, the positioning error will be estimated and the distance will be corrected. Otherwise, the mechanism will start moving along the surface to be examined. After the movement starts, the measurement of the spectrum reflected from the surface begins. During the measurement, the program works in a loop, constantly recording the obtained peak value of the spectrum and checking the condition for the end of the measurement. The exit condition is the end of the base segment. And when it occurs, the command to stop measurements and movement is executed, then the power of the spectrometer and LED is turned off. After that, the computer analyzes the data, displays the calculated roughness parameters and profilogram or records them in memory.

The algorithm for calculating the roughness parameters is shown in Fig. 6. First, the file is opened, the condition of opening and file integrity is checked. If the file is okay and not empty, the file is read and converted first to an array of type String, then to a list of type double. At this stage, the obtained values of the light wavelength are converted to the distance between the lens and the surface using the mathematical model (6). After that, the selected input parameters are checked and compared with the measured data. If the measured profile length is greater than the base length, it is reduced to the base length, and if it is the other way around, a request to change the base length is displayed. The next step is to build a graph within the base length. Next, the average line is calculated and plotted, relative to which the roughness parameters will be calculated. The next step is to calculate the parameters Ra and Rz and, after checking whether they are within the normal range, the corresponding results are displayed.

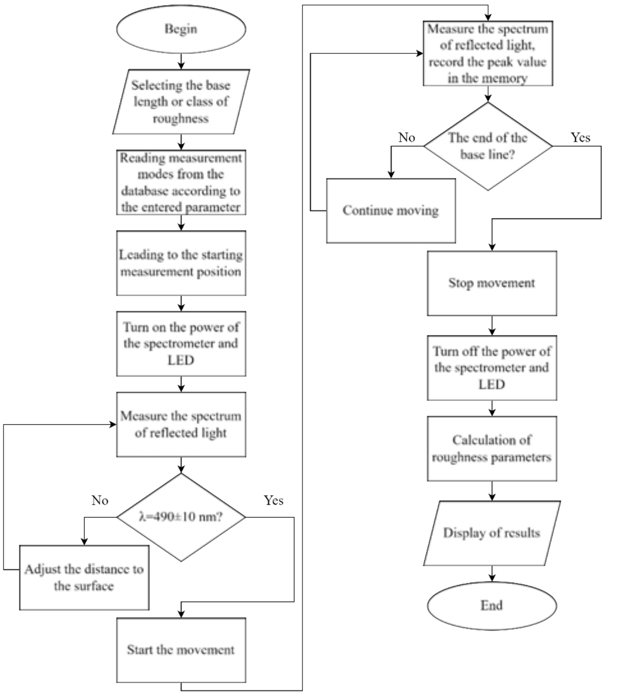

Fig. 5. Block diagram of the algorithm for measuring roughness parameters

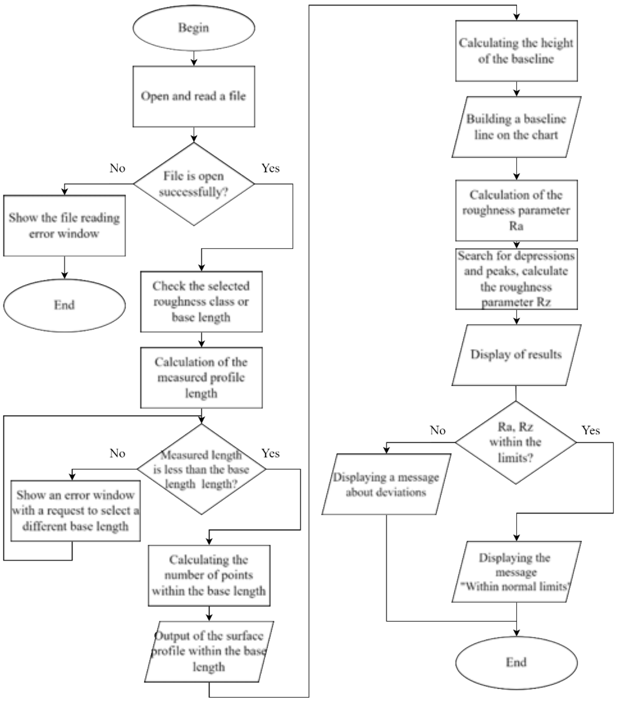

Fig. 6. Block diagram of the algorithm for calculating roughness parameters

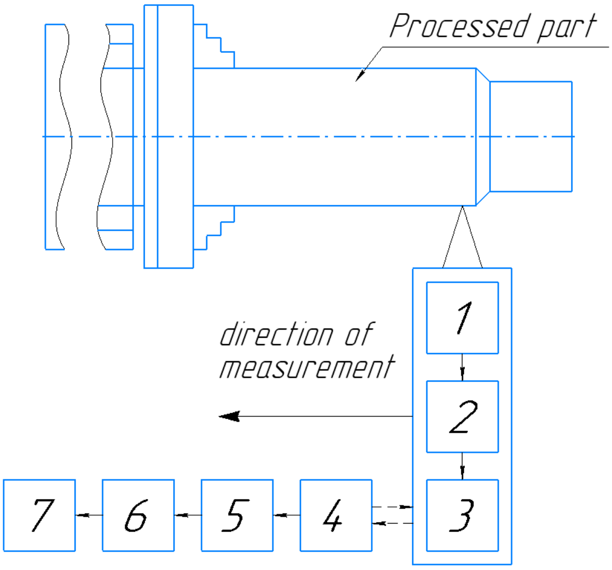

Fig. 7. Block diagram of the automated system for controlling the surface roughness of parts

The block diagram of the automated system for controlling the surface roughness parameters of parts is shown in Fig. 7.

Block 1 is the optical component of the automated system, which includes a white light source, a lens, a beam splitter, an aperture, and a spectrometer. The latter has a minimum integration time of 50 µs, which allows measurements with a frequency of up to 20 kHz. The speed of the caliper movement is set depending on the oriented roughness class or on the base measurement length (0.25–4 mm/s). During the measurement, the spectrometer measures the spectrum of the returned light and records the peak value of the spectrum at each moment of time in the memory (Block 2). Upon completion of the measurement, the recorded values are transmitted via a wired or wireless communication interface (Block 3 and Block 4) to a computer (Block 5). The latter calculates the roughness parameters and, using the comparison unit (Unit 6), evaluates whether the measured roughness parameters correspond to the specified ones. The last step is to display the results (Block 7). There is also a feedback between the spectrometer and the computer, which allows the computer to give a command to start and end measurements.

Compared to the profilograph, the chromatic confocal sensing method has an average error of about 5%. This makes it possible to measure the surface roughness with high accuracy with a Ra parameter of 0.2–0.7 [6].

Conclusions.

1. Based on the analysis of the state of the art and a review of existing solutions, it was decided to develop an automated system for monitoring the surface roughness parameters of parts using the optical method of confocal chromatic sensing. The advantage of this method is that it is non-contact, has high accuracy and speed of measurement;

2. Based on the analysis of sources and the method of confocal chromatic sensing, an automated system for monitoring the parameters of surface roughness of parts by the optical method was developed, elements of the optical component of the system were selected, and the focal lengths for different wavelengths of light for a flat-apochromatic lens were calculated using the tracing method, which showed that the difference in focal lengths for wavelengths of 380 nm and 700 nm is 0.45 mm;

3. Based on the calculation of focal lengths for different light wavelengths using the Lagrange interpolation formula, a mathematical model (6) was developed that established a nonlinear relationship of the focal length f_i on the wavelength λ_i, passing through the lens;

4. Based on the design of a confocal chromatic microscope, a structural diagram of an automated system for monitoring the parameters of the surface roughness of a part by the optical method was developed, which will allow measurements to be made in-situ, that is, without removing the part from the part holder;

5. On the basis of the developed mathematical model, an algorithm for the process of controlling and measuring roughness parameters was developed, which will allow measurements to be carried out in an automated mode, that is, in conditions of "unmanned production".

Bibliography:

1. В. Остаф'єв В.А., Тимчик Г.С., Шевченко В.В. Адаптивна система управління. Механізація і автоматизація управління.–Київ.– 1983, с.18-20.
2. Shunmugam M. S., Whitehouse D. J. Surfaces and surface metrology. *International Journal of Precision Technology*. 2013. Vol. 3, no. 4. P. 317. URL: https://doi.org/10.1504/ijptech.2013.058255 (date of access: 20.01.2024).
3. Alkhovyk O. V. Modern methods and means to control microgeometric parameters of surfaces of parts and devices. *Scientific Notes of Taurida National V.I. Vernadsky University. Series: Technical Sciences*. 2021. No. 3. P. 30–35. URL: https://doi.org/10.32838/2663-5941/2021.3/06 (date of access: 20.01.2024).
4. Roughness Measurement. *Encyclopedia of Tribology*. Boston, MA, 2013. P. 2967. URL: https://doi.org/10.1007/978-0-387-92897-5_101166 (date of access: 20.01.2024);
5. Chromatic Confocal Sensor Vs. Laser Displacement Sensor. *Chromatic Confocal Sensor Manufacturer*. URL: https://www.geramtech.com/chromatic-confocal-sensor-advantages/ (date of access: 20.01.2024).
6. Quinsat Y., Tournier C. In situ non-contact measurements of surface roughness. Precision Engineering. 2012. Т. 36, № 1. С. 97–103. URL: https://doi.org/10.1016/j.precisioneng.2011.07.011 (date of access: 20.01.2024).
7. HPCS300 Spectral Illuminance Sensing Module. *Hangzhou Hoptek Technology Co.,Ltd.* URL: https://www.hoptek.net/en/products/detail/300.html (date of access: 20.01.2024).
8. Microscope objective lens: patent 5729391 Japan : G02B 21/02; GO2B 9/12. No. 792,539 ; applied on 15.01.1997 ; published on 13.10.1998, Bulletin no. US005729391A. URL: https://patentimages.storage.googleapis.com/4c/c5/eb/0dacf0e01457d1/US5729391.pdf (date of access: 20.01.2024).
9. Hecht E. Optics, Global Edition. 5th ed. Pearson Higher Education & Professional Group, 2016. Vol. 5. 704 p. URL: https://emineter.files.wordpress.com/2020/04/hecht-optics-5ed.pdf (date of access: 20.01.2024).

Мельничук Б.П., Шевченко В.В. АВТОМАТИЗОВАНА СИСТЕМА КОНТРОЛЮ ПАРАМЕТРІВ ШОРСТКОСТІ ПОВЕРХНІ ДЕТАЛЕЙ

У статті представлено автоматизовану систему контролю параметрів шорсткості поверхні деталей за допомогою оптичного методу конфокального хроматичного зондування з проведенням вимірювань на місці.

Одними з найважливіших параметрів деталей є надійність та точність. Ці параметри безпосередньо залежать від параметрів шорсткості поверхні, тому важливо провести обробку деталей із заданими параметрами, що будуть відповідати призначенню деталі. Існує багато методів вимірювання параметрів шорсткості, більшість з них передбачають зняття деталі з верстату між операціями, в результаті чого в процес обробки деталі вноситься частина похибок, що пов'язані із установкою деталі. Також, звичайні методи та портативні прилади для вимірювання параметрів шорсткості часто неможливо використати для вимірювання деталей малих розмірів та складних геометричних форм.

В роботі використаний метод хроматичного конфокального зондування, що заснований на використанні явища дисперсії світла, тобто відображає залежність показника заломлення від середовища або частоти світла. Оптична система створена на основі конструкції конфокального хроматичного мікроскопа. Метод трасування променів був використаний з метою визначення фокусних відстаней для різних довжин світлової хвилі, що проходять через об'єктив. Після проходження об'єктиву біле світло розкладається в спектр, при цьому кожна довжина світлової хвилі фокусується на певній відстані від об'єктиву та утворює набір монохроматичних зображень. Метод множників Лагранжа був використаний для розробки та візуальної інтерпретації математичної залежності між фокусною відстанню та довжиною світлової хвилі. Таким чином за допомогою методу конфокального хроматичного зондування можна вимірювати геометрію поверхні та на основі вимірювань розрахувати параметри шорсткості. Також в роботі представлені та описані блок-схема алгоритму процесу контролю параметрів шорсткості, блок-схема алгоритму процесу вимірювання параметрів шорсткості та блок-схема автоматизованої системи контролю параметрів шорсткості поверхні деталей.

Автоматизована система контролю параметрів шорсткості поверхні деталей оптичним методом, з проведенням вимірювань на місці, дозволить підвищити точність вимірювань та продуктивність виробництва.

Ключові слова: *верстати з ЧПК, автоматизоване виробництво, параметри шорсткості поверхні деталей, вимірювання на місці, метод хроматичного конфокального зондування.*