Development of virtual roughness comparators

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Abstract. The surface roughness is inspected visually or by the contact profiling method. In both cases, actual roughness comparators with the preset roughness parameters (Ra) are used. The reference surface is created by various technological impacts. Technological processes are influenced by random factors; therefore, the reference surface has the deviations of the Ra parameter from the declared value. We suggest to control the roughness based on its image. In this case, the data available is not enough to determine the standard roughness parameters. We introduce the rough surface parameter ζ, which uses the standard parameters Ra and Rz.

We studied five images of roughness comparators made on glass using a New View 7300 white light interferometer. We determined the nominal value of the roughness parameter ζ for each roughness comparator and for each line of the rough surface images of 5 comparators. We considered the images of the reference surfaces as an indirect measurement of microrelief heights. We generated a reference rough surface based on the image of the actual surface of the roughness comparator. We used Spearman correlation coefficient to identify the most characteristic fragments of the reference rough surface. The virtual rough surface comparator created by us allows to increase the objectivity of visual control of rough surfaces and measure the similarity of the target and the reference rough surfaces.

1. Introduction

Visual (Fig. 1a) and contact control methods are used most widely to control rough surfaces of various natures [1–8]. Profile roughness control devices [1] require regular adjustment involving an actual roughness comparator (Fig. 1b, c) [2-8].

Image analysis of a roughness comparator surface (Fig. 2) showed that raster image pixels with the same values can correspond to different surface finish. The same heights obtained using a profilometer when measuring different longitudinal sections of a rough surface may also not mean that the heights of microroughness are the same. For these reasons, the reference rough surface in Fig. 2 may correspond locally to the declared roughness parameter Ra.

The Russian ruling document RTM 1.4.120-80 “Methods of surface roughness control” (NIAT, 1982) states: “when visually comparing the rough surfaces of a part and a sample (comparator, Fig. 1a), the relative error of control may exceed 70%.” We believe that a computer-generated roughness image shall be used as a reference rough surface (Fig. 1a). In this case, the generated image will not have the errors that random factors may form on the surface of an actual comparator (Fig. 1a). An image of the target rough surface is required to perform control by way of comparison. The generated
reference image and the image of the target surface should be obtained under equal conditions: illumination, spatial position of the camera, image size, color palette, etc.

**Figure 1.** Roughness comparators: a – roughness comparator formed by lathe turning for visual control (GOST 9378-93); b – roughness comparator for calibration of edge-reading roughness control gauges (GOST 2789-59); c - roughness comparator for calibration of edge-reading roughness control gauges (manufacturer: Mahr, Inc., Germany).

**Figure 2.** Roughness comparator image: a – actual comparator with $Ra = 0.16$ micron (magnification $\times 1000$); b – generated virtual comparator.

In order to quantify the similarity of the target and the reference rough surfaces, a parameter (hereinafter - $\zeta$) shall be defined, which corresponds to the following conditions:

- the rough surface parameter $\zeta$ is defined on the basis of the surface image;
- the parameter $\zeta$ is calculated on the basis of the existing standard roughness parameters (GOST 2789-73 “Surface roughness. Parameters and characteristics”) – this condition is necessary to maintain the consistency of data of the reference technical literature;
- the parameter $\zeta$ shall be dimensionless and scaled to enable the comparison of various roughness surface images.

On a generated surface comparator, the parameter $\zeta$ can be different for different lines and columns. This is possible when e.g. the matchmarks on the target surface are not parallel (rolls or swells) [9].

2. **Research objective**

The reference roughness is formed on a glass surface (Fig. 1 b, c). We obtained the image of microroughnesses with a white light interferometer ZYGO New View 7300 (Zygo Corporation, USA. Mailing address: 21 Laurel Brook Rd, Middlefield, CT 06455). The image magnification of microroughnesses was $\times 1000$. All the images of rough surfaces had the dimensions 239×258 pixels, and they were in grayscale with 256 grey gradations.
During the research we analyzed five images of roughness comparators (GOST 9378-93 “Roughness comparison specimens. General specifications”), with the following values of the roughness parameter $Ra$: 0.16; 0.17; 0.25; 0.32; 0.67 (μm).

We used the roughness parameters $Ra$ and $Rz$ standardized by GOST 2789 – 73 to define the new roughness parameter $ζ$. The reason for our choice was the fact that the parameters $Ra$ and $Rz$ are the height parameters.

We defined the roughness parameter $ζ$ in the following way:

$$ζ = 2 \sqrt{\log_{10}(Ra) \log_{10}(Rz)} / (\log_{10}(Ra + 1) + \log_{10}(Rz + 1) + 1)$$

(1)

For a flawless surface, when $Ra = Rz = 0$, $ζ \to 0$. For an absolutely rough surface, when $Ra \gg 0$ and $Rz \gg 0$, $ζ \to 1$.

GOST 2789-73 provides the relation between the parameters $Ra$, $Rz$ and the sample length $l$ ($l$ is the length of the line used to form the controlled roughness profile). It is clear from the GOST data, that the dependence $l = f(Ra, Rz)$ is ambiguous in nature (Fig. 3, line 1). This indicates that the dependence $l = f(ζ)$ is also ambiguous.

We propose to define the function $l = f(ζ)$ in such a way that its form is as close as possible to the form of the function $l = f(Ra, Rz)$, and for this purpose, the function $l = f(ζ)$ shall be single-valued (Fig. 3).

![Figure 3. Conversion of the function $l = f(Ra, Rz)$ to define a single-valued dependence between the roughness classes and the sample length $l$: 1 – ambiguous dependence between the roughness parameters $Ra$, $Rz$, $ζ$ and the sample length $l$; 2 – proposed single-valued dependence between $Ra$, $Rz$, $ζ$ and the sample length $l$; 3 – The scheme for determining whether the target surface image belongs to a certain roughness class based on the parameter $ζ$.](image)

In this case, based on the parameter $ζ$, we can define the corresponding value of the sample length $l$, which will determine whether the target microroughness belongs to a certain roughness class according to GOST with an accuracy to the pixel size. This means that the images of a geological surface with the resolution of a satellite camera and the images of a surface with an electron microscope resolution can have the same parameter $ζ$ and belong to the same roughness class.

We believe that the use of the parameter $ζ$ for parameterization of roughness is possible for the images of surfaces of the same resolution and the same nature. A scale should be placed on the optical surface of the recording device lens or in the recording plane to determine the size of objects in the image. In this case, the distance between the scale matchmarks should be known.

In order to determine the function $l = f(ζ)$, we calculated the limits of variation of the parameter $ζ$ for different sample lengths $l$ (or, according to the terminology of GOST 2789-59, for different roughness classes). We determined the roughness parameters $Ra$ and $Rz$ in accordance with GOST 2789-73, using the gray gradations of each pixel of image line or column.

Table 1 shows the correlation between the values of roughness parameters $Ra$ and $Rz$, different sample lengths $l$, roughness classes and the parameter $ζ$. When calculating the parameter $ζ$, the
standard values of Ra and Rz were measured in μm. To calculate the limits of variation of the parameter ζ for different roughness classes, we used the following conditions:
- for the roughness classes 1 to 7, the limits of variation of the roughness parameters are in the ratio \( Rz_{\min} = 4Ra_{\min} \) and \( Rz_{\max} = 4Ra_{\max} \)
- for the classes 8 to 14, \( Rz_{\min} = 5Ra_{\min} \) and \( Rz_{\max} = 5Ra_{\max} \).

**Table 1.** Correspondence between the values of the roughness parameters Ra and Rz, sample lengths \( l \), roughness classes and the parameter ζ.

| Ra, μm | Rz, μm | Sample length \( l, \mu m \) | \( \bar{l}/l_{\max} \) | Roughness class | ζ      |
|-------|-------|-----------------|-----------------|----------------|--------|
| 80-100| 320-400| 25000           | 1               | rougher-1       | 0.8078 - 0.8147 |
| 40-80 | 160-320| 8000            | 0.32            | 1-2             | 0.7829 - 0.8078 |
| 20-40 | 80-160 | 8000            | 0.32            | 2-3             | 0.7510 - 0.7829 |
| 10-20 | 40-80  | 2500-8000       | 1-0.32          | 3-4             | 0.7093 - 0.7510 |
| 5-10  | 20-40  | 2500            | 0.1             | 4-5             | 0.6543 - 0.7093 |
| 2.5-5 | 10-20  | 800-2500        | 0.032-0.01      | 5-6             | 0.5823 - 0.6543 |
| 1.25-2.5 | 6.3-10 | 800            | 0.032          | 6-7             | 0.5237 - 0.5823- |
| 0.63-1.25 | 3.2-6.3 | 800            | 0.032          | 7-8             | 0.4247 - 0.5237 |
| 0.32-0.63 | 1.6-3.2 | 250-800        | 0.01-0.032     | 8-9             | 0.3155 - 0.4247 |
| 0.16-0.32 | 0.8-1.6 | 250            | 0.01           | 9-10            | 0.2131 - 0.3155 |
| 0.08-0.16 | 0.4-0.8 | 250            | 0.01           | 10-11           | 0.1310 - 0.2131 |
| 0.04-0.08 | 0.2-0.4 | 250            | 0.01           | 11-12           | 0.0744 - 0.1310 |
| 0.02-0.04 | 0.1-0.2 | 80-250         | 0.0032-0.01    | 12-13           | 0.0401 - 0.0744 |
| 0.01-0.02 | 0.05-0.1 | 80             | 0.0032        | 13-14           | 0.0208 - 0.0401 |

We suggest the following procedure to determine whether the image of microroughnesses belongs to a certain roughness class:
- define an unambiguous correspondence between the values of Ra, Rz and the sample length \( l \) of various roughness classes using the polynomial dependence
  \[
  l = \sum_{i=1}^{n} a_i Ra^{i-1},
  \]
  where \( a_i \) is the polynomial constants determined by the polynomial degree \( n \) (using \( n = 12 \)); \( l \) is the value of the sample length. The approximation accuracy is determined by the required accuracy of defining the class of the rough surface;
- the values of sample lengths are subject to standardization \( \bar{l} \) (Fig. 3, line 2);
- align the values of ζ and the roughness parameter Rz (or Ra) at the boundaries of different roughness classes.

We suggest to determine the roughness class in the image of a surface with microroughnesses according to the value ζ, which we put in unambiguous correspondence with the roughness parameter Ra, Rz (1), which corresponds to the boundaries of the roughness classes. Further, based on the parameter ζ and the curve 2 (formula (2)), we determine the roughness class in the image of the target surface (Fig. 3, line 3).

When calculating the parameter ζ, the values of the parameters Ra and Rz should be within the same class (Table 1).

The division of roughness classes from 6 to 14 into 64 categories in accordance with GOST 2789-59 allows to increase the accuracy of parameterization of a rough surface image.

There are the correlation methods for evaluation of surface microroughnesses based on its image [10]. We believe that the disadvantage of these methods is the difficulty of interpreting the results with regard to the roughness parameters (Ra, Rz) defined by the standards.

The choice of the type of the new roughness metric ζ is determined by the following reasons:
- in terms of production or medical practice, the use of a white light interferometer to control the roughness is associated with significant difficulties (technical, financial, etc.).
- an image of a rough surface obtained by another method, for example, using a camera, does not contain information about the absolute values of the geometry of microroughnesses, therefore it is impossible to use the standard roughness parameters;

- in case of generating an image of a reference rough surface of various nature, it is necessary to have a roughness parameter that can determine the difference between the reference and target surfaces quantitatively.

We suggest to use virtual images of a roughness comparator to control the roughness. We have generated an image of a roughness comparator on the basis of the image shown in Fig.1. We will consider that the image is a matrix \( I = [a_{ij}]_{m,n} \), where \( a_{ij} \) is the brightness (grey gradation from 0 to 255) of a pixel with the coordinates \( i \) and \( j \), \( m \) and \( n \) are the quantity of lines and columns of the image \( I \) correspondingly. The distribution of brightness of pixels along the image \( I \) lines and columns is different from the standard distribution, that is why we used the Spearman's rank correlation coefficient \( (\rho) \) [11-12] to define the correlation between the lines of the image \( I \). We generated the roughness comparator for the statistical significance \( \alpha = 0.01 \). We calculated the parameter \( \zeta \) only for the lines of the generated image. The arrows in the Fig. 1b show the direction of roughness measurement on the comparator, which corresponded to the direction of the image lines in the Fig. 2a.

We generated the image of the roughness comparator in the following way:

- the image lines were defined \( S_i = \{a_{ij}: j = 1, n\} \), for which \( \rho_{ij} \geq 0.7 \) and \( i \neq j \);

- for each of the lines chosen \( \{S_k, S_l, S_p, ..., S_t\} \) the sequences of pixels were defined \( \{s_r, s_{r+1}, s_{r+2}, ..., s_{r+f_r}\} \) for \( f = \{k, l, p, ..., t\} \), which occur in the line most often;

- the sequence \( \Omega \) is added to the sequence of pixels \( \Omega \) until the total length of the sequence of pixels differs minimally from the length of the lines of the image \( I \). The lines generated like this is then attached to each other until the matrix generated like this has the number of lines equal to the number of lines of the raster image \( I \).

3. Research results
We grouped the characteristics of five actual roughness comparators.

1. The analysis of the values of \( \zeta \) for the lines and columns of the roughness comparator shown in the Fig. 2a gave the following results:

a) the parameter \( \zeta \) takes on the values corresponding to different sample lengths \( l \), in other words, to different roughness classes (Fig. 4);

b) the parameter \( \zeta \) takes on the values corresponding to different sample lengths \( l \) from 250 to 2250 \( \mu m \), in other words, to roughness classes from 4 to 10 (Fig. 5);

c) most often, the values of the parameter \( \zeta \) correspond to the base length \( l=250 \mu m \) (6-8 roughness class according to GOST 2789-59 “Surface roughness. Parameters and characteristics” or \( Ra \subset [0.4; 2.5] \mu m, Rz \subset [2.0; 10.0] \mu m \)). In 66% of cases the values of \( \zeta \) correspond to the roughness class 5-6 (\( Ra \subset [1.6; 5.0] \mu m, Rz \subset [4.0; 8.0] \mu m \)). It should be noted that the rated values of the reference surface in Fig. 2a correspond to the 9th roughness class (\( Ra \subset [0.2; 0.32] \mu m, Rz \subset [1.0; 1.6] \mu m \)). Fig. 4 shows the fluctuations of the parameter \( \zeta \) by the columns and lines of the image of the roughness comparator with \( Ra = 0.16 \mu m \);

d) the values of \( \zeta \) calculated for the columns have more uniform distribution.

2. A similar discrepancy of the parameters \( Ra, Rz \), the sample length \( l \) and the roughness parameter was observed in another 4 roughness comparators with \( Ra \) equal to 0.17; 0.25; 0.32; 0.67 \( \mu m \).

3. The roughness parameter \( \zeta \) for each column of the image in Fig. 2b is equal to 0.446 (the statistical significance \( \alpha = 0.01 \)).

4. The roughness parameter \( \zeta \) for each line is equal to 0.446 (statistical significance \( \alpha = 0.01 \)).

The method suggested can be used, for example, for visual inspection and analysis of surface roughness after laser finishing of hard-to-machine materials [13-14].
The accuracy of control of rough surfaces is influenced greatly by the characteristics of the optics used. The choice of the recording device lens should be based on a priori information about the geometric dimensions of microroughnesses of the reference and the target rough surfaces. If the target microroughnesses have small height, a high-resolution lens shall be used. In this case, the image of the rough surface has a relatively small depth of field. A higher magnification creates a greater depth of field in the controlled plane. The need for such a situation arises when controlling biological surfaces [15]. The procedure of parfocal image straightening shall be used in case of high magnification of the target surface. We plan to continue research in this direction.

4. Conclusion

The use of the method developed will allow to increase the objectivity of roughness control by the sample.

The use of the parameter $\zeta$ allows to quantify the “similarity” of images of the reference and the target rough surfaces.

Calculation of the limits of the parameter $\zeta$ variation for the ranges of correspondence of the standard parameters $Ra$ and $Rz$ (GOST 2789-73) leads to the emerging of $\zeta$ intervals that do not correspond to any of the standard ranges of variation of $Ra$ and $Rz$. For this reason, we have chosen the nonlinear relationship (2) between the values $\zeta_l$ and $\zeta$. Therefore, it is advisable to change the limits of correspondence of the values of the parameters $Ra$, $Rz$ and the sample length $l$ to a certain
roughness class provided by the standard. We are going to continue the research in this direction and publish the results in the next article.

The method analyzed can be used to control rough surfaces of various nature, for example, the biological ones [15-16]. The generation of a reference rough surface of a biological object (for example, bone tissue on an X-ray image) requires an algorithm that reveals the most characteristic features of microroughnesses in image fragments, not in image lines. In this case, it is necessary to determine the distribution of grey gradations for each fragment, as well as the peculiarities of its structure (for example, the presence of extensive rolls or swells). The method developed can take an important part when controlling the roughness of diffraction micro-reliefs formed by electronic, plasma, laser, mechanical and other methods [17-28]. We plan to increase the capabilities of the virtual comparator and the accuracy of roughness class assessment using a LED-based structured-light system [29-36].

5. References

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