Optical properties of component surfaces processed by surface plastic deformation methods

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Abstract. It is suggested in this paper that parameters characterizing the reflectivity of machine component surfaces are used as indicators of surface quality. The research results of influencing technological factors of surface plastic deformation processing on these parameters are presented.

1. Problem Statement
The reflectivity parameters of the component surface can be considered as operational characteristics, and for a comprehensive assessment of the state of the surface roughness profile, when they are regulated in the technical documentation. In the simplest case, the reflectivity can be characterized by brightness [1].

For study and microanalysis of the structure of the component surfaces, the team of Bryansk State Technical University developed a system for microstructural surface analysis based on the modular construction principle with open source software (figure 1). Metallographic microscopes (MIM-10, Metam RV, etc.) or microhardness tester (PMT-3M, etc.) are used to register fragments of component surfaces. The received information is transmitted to the computer via an optical matching device and photo-video equipment for subsequent processing of the received information using special software (e.g. Image Scope Color, etc.), which allows determining various surface characteristics [2]. Also, a computerized scanning microscopy system on the basis of an inverted metallographic microscope Leica DM IRM HC was used to study the component surfaces with a quantitative assessment of topographic parameters.

Data on geometric and optical characteristics of the surface were presented as: 1) surface micrographs that characterize its topography as a qualitative assessment; 2) profile records and values of surface roughness parameters; 3) brightness histograms that characterize the relative distribution of brightness across surface areas in the selected measurement area; 4) a brightness profile that shows the quantitative change in surface brightness along the measurement route (figure 2).

Visual similarity between the roughness and brightness profiles justifies the expediency of including surface profile record in the results of its analysis, which was implemented for various variants of technological impact on the surface (figure 2) [3]. On the micrograph of the flat component surface (steel 45), lines A and B are indicated, which are the routes for measuring the roughness parameters and optical characteristics after face milling with composite 10 (route A) and subsequent diamond burnishing (route B). The figures indicate reference points for comparing profile records and the brightness profile.
Brightness histograms and its profile for different stages of technological impact on the processed surface differ significantly from each other (figure 2a, b). Maximum profile values of brightness histogram are typical for surface areas with light tones. Processing by surface plastic deformation (SPD) methods, such as diamond burnishing (DB), allows forming surfaces characterized by high reflectivity, which can be seen on the brightness histogram – the maximum number of surface areas corresponds to the maximum brightness.

Analysis of brightness distribution histograms after various methods of technological impact on the surface revealed the following features:

1. When milling flat surfaces, there is a multimodal histogram with three vertices that correspond to high, medium, and low brightness. These vertices have the character of local extremes and can be attributed to the reflectivity peaks, the sides of the asperities and profile valley of roughness, respectively.

2. Flat grinding contributes to the formation of a single-modal brightness histogram with a maximum shift towards light tones (mode) and the presence of a characteristic bevel to dark tones.

3. SPD processing with small forces contributes to the formation of a flat-topped histogram of surface brightness, that is, it has a trapezoidal shape.
4. If to process with diamond burnishing, the original brightness histogram is transformed by shifting its mode towards light tones. Thus, the surface brightness depends on the methods of technological impact, and its parameters can be controlled technologically [4, 5].

The task was set to construct physical-statistical models for quantifying the influence of component processing factors by SPD methods on the parameters of surface reflectivity.

2. Study Results

Technological control of a certain value is possible if it has unit measure for quantitative evaluation. Brightness histograms and corresponding surface brightness profiles are constructed for black and white tones in computerized measurement systems (figure 1).

One of the indicators of the component surface quality is its reflectivity. Its technological support is necessary if the relevant quantitative characteristics are regulated in the technical documentation.

If the color saturation scale is 8bit, pure white has a brightness rating of $E_{\text{max}} = 2^8 - 1$, and black has a brightness rating of $E_{\text{min}} = 0$. It is within these limits that the surface brightness changes in histograms and brightness profiles. Since this scale is not very convenient for practical purposes (instability of the light source, illumination angle, etc.), it is proposed to normalize the actual value of surface brightness $E$ by maximum value $E_{\text{max}} = 255$ and enter a brightness coefficient to assess the reflectivity of the surface after processing:

$$R_e = \frac{E(x)}{E_{\text{max}}},$$

where $x$ is the surface coordinate under study on the measurement route.

We get a dependency graph $R_e = f(x)$, which is identical in shape to the brightness profile, but $R_e$ value theoretically changes between 0 and 1: pure black color is $R_e = 0$; pure white color is $R_e = 1$.

The introduction of a relative assessment of the surface reflectivity by the value of the brightness coefficient $R_e$ allows to neutralize the influence of the instability of external illumination of the surface on the measurement results in the course of research. This allows to compare correctly both the results obtained using various systems of microstructural analysis of the component surfaces, and by different researchers [3, 6, etc.].

For $R_e$ value it is advisable to enter the following numerical characteristics:

1. Maximum $R_{\text{max}}$ and minimum $R_{\text{min}}$ values of the brightness coefficient and its maximum difference $\Delta(R_e)$:

$$\Delta(R_e) = R_{\text{max}} - R_{\text{min}}.$$  

2. Arithmetic mean of the brightness coefficient:

$$\overline{R_e} = \frac{1}{n} \sum_{i=1}^{n} R_{ei},$$

where $R_{ei}$ is $i$-value of $R_e$ in a series of $n$ measurements.

$\overline{R_e}$ value quantifies the average brightness or average tone of the surface in black and white shades.

3. Mean square deviation of the brightness coefficient:

$$\sigma(R_e) = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} (R_{ei} - \overline{R_e})^2}.$$  

This parameter characterizes the spread of the brightness coefficient as a random value on the measurement route.

4. Coefficient of brightness variation:

$$\gamma = \frac{\sigma(R_e)}{\overline{R_e}}.$$
The coefficient of variation is a measure of relative variability and, in this case, allows to evaluate the nature of the distribution of the surface brightness coefficient.

Some typical study results of forming reflectivity (brightness) of flat surface samples made of cast iron SCH20 during processing by various SPD methods are presented in figure 3.

Figure 3. Study results of surface reflectivity of the workpiece made of cast iron SCH20 after finishing and strengthening processing with diamond burnishing (a, c) and ball burnishing (b, d) with intender radius \( r_{\text{ind}} = 3.5 \) mm: 1 – surface micrograph; 2, 3 – brightness coefficient and histogram of its distribution; FM – face milling; DB – diamond burnishing; BB – ball burnishing

The presented values of \( \bar{Re} \) brightness coefficient indicate that SPD processing by diamond burnishing method contributes to an increase of surface reflectivity in comparison with ball burnishing, other things being equal. At the same time, the brightness spread over the surface, characterized by \( S\{Re\} \) value, is in all cases less than when processing by ball burnishing.

Variation coefficient \( \gamma \) is also significantly lower for diamond burnishing than for ball burnishing. Histograms of brightness distribution in cases of diamond burnishing have a much smaller spread and a greater maximum shift in the direction of increasing brightness than with ball burnishing, other things being equal.

Thus, diamond burnishing improves the surface reflectivity more effectively, compared to ball burnishing.

Similar results were obtained while studying the effect of SPD processing conditions on the reflectivity of flat component surfaces made of steel 45.

Identifying the statistical interconnection between the brightness parameters and the surface profile can contribute to the development of compact electro-optical devices for measuring and recording the profile parameters of the processed surface in production conditions.

Statistical models such as Cobb-Douglas functions were used to quantify the degree of influence of technological processing factors by various SPD methods on forming the following parameters \( \bar{Re} \), \( S\{Re\} \), \( \Delta Re \), \( \gamma \), that characterize the reflectivity of the surface [2, 5, 7, 8]:

\[
Y_i = \beta_0 X_1^{\beta_1} X_2^{\beta_2} \ldots X_k^{\beta_k},
\]  
(6)
where $Y_i$ is the $i$-parameter of the surface reflectivity; $X_i$ is the $i$-factor that affects forming the reflectivity parameter in the conditions of the given experiments; $\beta_0$, $\beta_i$ are the true values of regression coefficients.

The obtained statistical models are presented as the following dependency:

$$Y_i = b_0 X_{pre}^{b_1} Q^{b_2} S^{b_3} K_i.$$  \hspace{1cm} (7)

During the experiments, the influence of the following technological factors was studied:

- $Ra_{pre} = 1.57 – 3.1 \mu m$ is an arithmetic mean deviation of the roughness profile from the surface mean line after preliminary face milling by composite 10;
- $Q = 50 – 100 N$ is the indenter force of SPD tool on the processed surface;
- $S = 0.07 – 0.7 \text{ mm/ind}$ is the tool feed speed during SPD processing.

$K_i$ coefficient takes into account the influence of diamond burnishing or ball burnishing methods. SPD processing was performed with a single-indenter elastic tool [2].

$b_0$, $b_1$, $b_2$, $b_3$, $K_i$ included in the model (7) are shown in the table 1.

Table 1. Parameter values of models for forming indicators of surface brightness of components made of cast iron SCH20 after SPD processing by diamond burnishing and ball burnishing

| Indicators of surface brightness | Model parameters (7) | $K_i$ |
|----------------------------------|----------------------|-------|
|                                 | $b_0$    | $b_1$    | $b_2$    | $b_3$    | Diamond burnishing | Ball burnishing |
| $Re$                            | 0,46     | -0,21    | 0.085    | -0,01    | 1,27               | 1,11              |
| $S(Re)$                         | 0,41     | 0,35     | -0,12    | 0,034    | 0,45               | 0,71              |
| $\Delta(Re)$                    | 0,87     | 0,15     | -0,03    | 0,024    | 0,82               | 0,92              |
| $\gamma$                        | 0,89     | 0,56     | -0,2     | 0,05     | 0,35               | 0,64              |

The results of experiments showed that SPD processing by diamond burnishing contributes to a significant increase in the parameters of the relative brightness of the processed surface. SPD technological factors ($Ra_{pre}$, $Q$, $S$) also have a significant impact on the parameters of relative brightness, which is proved by the comparison of the calculated value of Student's $t$-test with the table value $t_{0.05} = 2.78$.

3. Conclusion

The considered methods and research results relate only to specific conditions for SPD processing of flat component surfaces and can serve as an approximate reference point for more detailed research in the field of technological support of reflectivity parameters of component surfaces by various processing methods.

It should be noted that the identification of a reliable statistical interconnection between the brightness parameters and the surface microprofile can contribute to the development of compact electro-optical devices for measuring and recording the microprofile parameters of the processed surface in production conditions.

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