Modeling of process of forming quality parameters for surfaces of parts by diamond burnishing taking into account technological heredity

M N Nagorkin, V P Fyodorov, E V Kovalyova

Bryansk State Technical University, 7, 50 let Oktyabrya Blvd, Bryansk, 241035, Russia

E-mail: nagorkin_mn@mail.ru

Abstract. The paper presents a methodology for quantitative assessment of the influence of technological heredity on the formation of quality parameters for surfaces of machine parts. An example of an estimation of influence factors of technological subsystems of processing by end milling processing by composite 10 and the subsequent diamond burnishing is presented.

1. Introduction

The final formation of surface layer quality parameters of machine parts is carried out basically at the final stages of the technological process of processing workpieces: finishing operations, with the significant role belonging to the mechanism of technological inheritance [1 – 5]. The degree of technological inheritance influence is ambiguous depending on the conditions of both preliminary and final processing. In the work the technique of calculation of factors of influence of successive technological systems of finishing and finishing surfaces on parameters of their quality quantitatively reflecting technological heredity is offered.

2. Materials and methods

The technological system (TS) of diamond burnishing (DB) of flat surfaces of gray cast iron (SCh20) parts, used in the manufacture of basic elements of equipment and technological equipment after preliminary face milling (or flat grinding), was considered as an object of research.

Pre-treatment by face milling was carried out using standard incisal inserts equipped with composite 10 at angles \( \varphi = 45^\circ, \varphi_1 = 30^\circ \), in modes providing surface roughness parameters \( R_{a_{pr}} = 10; 5; 1 \mu m \).

DB carried out by an elastic tool with a peripherally located indentor made of polycrystalline diamond of ASPC (carbonado) type (radius of the vertex is 3 mm). The power of diamond burnishing varied within \( Q = 50…150 \) N [5].

3. Results and Discussion

In the model of the DB process, proposed by prof. LA Khvorostukhin (Fig. 1) [6], it is assumed that maximum roughness height \( R_{max} \) of the pretreated surface under certain processing conditions is less than the value of the plastic deformation of surface layer \( \Delta H \). This assumption was experimentally confirmed by simultaneous measurement of roughness parameters of the surface areas of samples after
preliminary processing by milling with composite 10 (sections A) and subsequent DB (section B, figure 2) with the indicated modes.

**Figure 1.** Diamond burnishing of a surface of a detail made of cast iron: 1 – rough surface; 2 – lubricating-cooling technological agent; 3 – diamond indenter; 4 – graphite inclusions in the cast iron metallic base; 5 – ironed surface; 6 – graphite particles displaced from the deformation zone

| Milling modes (section A): | | | |
|---------------------------|--|---|---|
| \(S_{mil}\) = 0.25 mm / tooth; | \(V_{mil}\) = 622 m / min; | \(Ra_{mil}\) = 11.5 \(\mu\)m |

| DB modes (section B): | | | |
|----------------------|--|---|---|
| \(Q\) = 150 N; | \(S_{DB}\) = 0.025 mm / rev; | \(V_{DB}\) = 35.2 m / min; | \(Ra_{DB}\) = 1 \(\mu\)m; \(\Delta H\) = 65.4 \(\mu\)m |

**Figure 2.** Typical profile record for determination of permanent deformation surface of the cast iron part after face milling with composite 10 and DB

On the flat surfaces treated by diamond burnishing, the following characteristic areas can be distinguished (Figure 3): \(\alpha\) – surface after pretreatment; \(\beta\) – surface after diamond burnishing without traces of crossing (input and output of the corresponding transition); \(\gamma\) – the main part of the ironed surface. In addition, we can consider the transitions between different parts of the surface: \(\alpha\)-\(\beta\), \(\alpha\)-\(\gamma\), \(\beta\)-\(\gamma\). Surface area \(\gamma\) is the most characteristic and important for the formation of the operational properties of the surfaces to be treated.

The dark background in the presented micrographs of the flat surface sections (Figure 3) reflects the presence of graphite inclusions in the material of the samples, light – their absence (or a small number).

The analysis of microphotographs shows that the continuity of the surface layer depends both on the roughness of preliminary treated surface \(Ra_{pr}\) = 1 – 10 \(\mu\)m, and on burnishing force \(Q\) = 30 – 150 N.

The following is established: 1) for roughness of initial surface \(Ra_{p}\) = 3 – 10 \(\mu\)m, angle \(\Delta\) between the burnishing indenter velocity vectors and the tip of the cutting part of the cutter tooth affects the continuity of the ironed surface; 2) with a decrease in the roughness of the pretreated surface to \(Ra_{p}\) = 2 \(\mu\)m and lower, the influence of the velocity vector on the change in the continuity of the surface is not determined.

Hence, to ensure high surface continuity, it is advisable to carry out preliminary processing with a low roughness, or to increase angle \(\Delta\) between the pre-treatment velocity vectors and DB (Fig. 3). The first option leads to higher costs, and the second - to optimizing the diameter of the end mill and the diameter of the indenter in the diamond burnishing tool. The second option is economically more efficient.

The methods of physical-statistical modeling based on the use of simulation models of processing processes [5, 7, 8] make the basis of the research of technological maintenance of quality parameters and operational properties of surfaces of machine parts.
Physical-statistical models for the formation of roughness parameters of flat surfaces of details from cast iron ($Ra$, $Rz$, $R_{max}$, $R_p$, $S_m$, $\rho$, $b$, $v$, $\Delta$) are obtained. These models are correct in the following boundaries of the factor space of the considered TS: $S_{mil} = 0.05 – 0.25$ mm / tooth; $V_{mil} = 311 – 622$ m / min; $Q = 50 – 150$ N; $S_{DB} = 0.025 – 0.16$ mm / rev; $V_{DB} = 35 – 90$ m / min. When investigating technological controllability by the DB quality parameters, the grinding conditions were selected to provide a roughness of $R_{a} = 0.16 – 0.6 \ \mu m$ [5].

Consideration of the variation intervals in the roughness parameters of the surfaces of the parts from the cast iron during the experiments for different processing methods shows a rather wide range of their variation with diamond burnishing after preliminary face milling. This is especially true for parameters $Ra$, $R_p$, $R_z$, $R_{max}$, $S_m$ and $\Delta H$.

An important issue is the study of the influence of the quality parameters of flat surfaces obtained during preliminary processing on the formation of the corresponding parameters after the final processing, which characterizes the degree of technological inheritance. Corresponding correlation links were analyzed. Solving this issue will allow us to choose the minimum number of quality parameters required for their technological provision reasonably.

The analysis of correlation graphs revealed almost 100% correlation between all standardized parameters of roughness. To reveal the linear relationships, it is necessary to consider statistically insignificant correlation links, but correlation links with pair correlation coefficient $r$ close to 1.

The process of forming a surface micro-profile by superficial plastic deformation methods depends both on the state of the pretreated surface and on the factors of the method itself, in particular diamond burnishing, which causes a decrease in the average degree of the vertices of correlation graphs at high values of $r$ [5, 7]. The statistically significant value of the pair correlation coefficient is $r = 0.2$. The changes in the characteristics of the correlation graphs of the quality parameters as a function of the growth of the coefficient $r$ were analyzed. Some of them are shown in Fig. 4.
Figure 4. Graphs of correlation links between the roughness parameters of surfaces of cast iron parts machined by face milling and surface parameters treated with subsequent diamond burnishing

The graph in Fig. 4a is densely saturated with statistically significant correlations ($r = 0.2$). With increasing $r$, the number of corresponding correlations both positive and negative decreases ($r = 0.8$, Fig. 4b). The analysis of the characteristics of the graphs for the corresponding coefficients of pair correlation showed that the average degree of the vertex reflecting the influence of the $i$-th initial surface quality parameter on the qualities formed during diamond burnishing changes from $8 - 11$ (at $r = 0.2$) to $0$ (for $r = 0.9$). Such sharp decline in the average degree of the peak is obviously affected by the nonlinearity plastic deformations of the surface metal occurring during the process of ironing. In this connection, it is advisable to reflect such connections by nonlinear dependencies.

During the part surface processing, the process of its evolution from the initial to the technological takes place (Figure 5) [5, 9 – 11].

Figure 5. Scheme of evolution of quality parameters of surfaces of machine parts during processing in $q$ technological systems

In general, the technological process can contain $q$ technological systems (TS), whose input parameters, for example for TS$_e$, are surface quality parameters after the previous processing step ($Y_{i(e-1)}$), control conditions are processing conditions ($X_{e1}$, $X_{e2}$, ..., $X_{eξ}$), and the output parameters are the obtained surface quality parameters ($Y_{ie}$).

In order to quantify the impact of technological heredity on the formation of quality parameters during processing, it is advisable to apply the simulation method. It is logical to use the Cobb-Douglas models, since calculations on them do not give negative values of the parameters, that is, the physical picture of their formation is not violated [5, 7].

For quality parameter $Y_{ie}$, formed at the stage of surface evolution in the TS$_e$ system, the simulation model generally has the form:
factors on formation of quality parameters of a surface in TS «end milling by composite 10 – DB» for various areas of factorial space is generated.

quality parameters final value all the studied points in the region of the factor space contribute to its increase from 1.52 to 5.05 times. That is, technological heredity, on the formation of investigated quality parameters. Influence coefficient characterizing the effect of diamond burnishing modes ranges from 0.03 to 0.16. For model (1), condition 2 is fulfilled:

\[ Y_i = Y_{i0} \cdot \prod_{j=1}^{\mu} X_{1j}^{b_{1j}} \cdots \prod_{m=1}^{\xi} X_{em}^{b_{em}} \cdots \prod_{\zeta=1}^{\psi} X_{qs}^{b_{qs}}. \]  \( (1) \)

Here \( Y_{i0} \) – the average experimental value of the \( i \)-th quality parameter, which has a corresponding dimension and is determined by the results of the active experiment; \( X_{em} \) is a parameter numerically equal to the value of the \( m \)-th processing factor in TS\(_q\); \( b_{em} \) is the exponent corresponding to processing factor \( X_{em} \).

For model (1), condition 2 is fulfilled:

\[ \mu + \xi + \psi = k, \]  \( (2) \)

where \( k \) – the total number of factors considered in the process in terms of active experiment.

Proceeding from this, in accordance with Fig. 5 in the general case there is:

\[ Y_i = Y_{i0} + Y_{i1} + \ldots + Y_{i\mu} + \ldots + Y_{i\psi}. \]  \( (3) \)

\[ Y_{i1} = \left( \sum_{j=1}^{\mu} b_{1j} X_{1j} \right) ; \ldots ; Y_{i\mu} = \left( \sum_{m=1}^{\xi} b_{em} X_{em} \right) ; \ldots ; Y_{i\psi} = \left( \sum_{\zeta=1}^{\psi} b_{qs} X_{qs} \right). \]  \( (4) \)

\( Y_{i1}, \ldots, Y_{i\psi} \) – the contribution of technological process subsystems TS\(_{1}, \ldots, \)TS\(_{q}\) to the formation of quality parameters final value \( Y_i \).

It is assumed that value \( Y_{i1}, \ldots, Y_{i\psi} \) must have the dimension of \( Y_i \).

Dependence (1) can be represented in the form of (5):

\[ Y_i = Y_{i0} \cdot K_1 \cdot \ldots \cdot K_\psi. \]  \( (5) \)

Here \( K_1, \ldots, K_\psi \) – coefficients of influence of the corresponding TS:

\[ K_1 = \prod_{j=1}^{\mu} X_{1j}^{b_{1j}} ; \ldots ; K_\psi = \prod_{\zeta=1}^{\psi} X_{qs}^{b_{qs}}. \]  \( (6) \)

Thus, from the values of coefficients \( K_\psi \), one can judge the influence of technological subsystems, that is, technological heredity, on the formation of the investigated quality parameters. Influence coefficient \( K_\psi \) in the general case can be represented in the form (7):

\[ K_\psi = k_{q1} \cdot k_{q2} \cdots k_{q\psi}. \]  \( (7) \)

Here, \( \psi \) – number of control factors of the technological subsystem TS\(_q\).

For the convenience of analyzing technological heredity influence on the formation of the investigated parameters, it is advisable to logarithmize the expression (7).

The proposed approach to assessing the impact of technological heredity can differentially address the selection of processing factors by \( k_{q\psi} \) values for the effective management of regulated quality parameters. Preference is given to factors with higher values of \( k_{q\psi} \).

Graphical representation of technological heredity influence on the formation of micro profile parameters (Figure 6) shows that it is different for each parameter and for different points of the factor space region. For example, for parameters Ra, the \( K_1 \) coefficient, which characterizes the influence of the pretreatment modes in the investigated region of the factor space, ranges from 2.36 to 16.24, and the \( K_2 \) coefficient characterizing the effect of diamond burnishing modes ranges from 0.03 to 0.16. That is, due to the effect of the DB modes, the Ra parameter, for example, can be changed by more than 30 times relative to the average experimental value \( R_{a0} = 2.88 \mu m \), and the pretreatment factors at all the studied points in the region of the factor space contribute to its increase from 1.52 to 5.05 times.

A similar analysis was carried out for other parameters.

On the basis of the conducted research the database of values of technological heredity influence factors on formation of quality parameters of a surface in TS «end milling by composite 10 – DB» for various areas of factorial space is generated.
4. Conclusion

On the basis of simulation modeling of the process of forming parameters for the quality of the surfaces of parts at various stages of processing, a methodology for quantifying the impact of technological heredity was proposed. Coefficients of influence that take into account the processing conditions at the preliminary and final stages make it possible to evaluate which processing factors contribute more to the formation of quality parameters, which will improve the manageability of the processes of forming quality parameters.

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