Modeling a 3D surface roughness of mating parts produced with lathe turning

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Abstract. This paper presents operation of a newly-developed software providing visualization of topography of a machined surface on the basis of ISO 25000 standard and taking into account physical and mechanical properties of material, as well as changes in the surface during the green run.

1. Introduction

Mechanical engineering and aviation industries use various technological methods to ensure predefined parameters of surface quality of parts, with considerations for the required operating conditions, including heating temperature, operating loads, environment, duration of physical and chemical exposure. For example, surface roughness determines not only contact rigidity, fatigue point and durability, but is also interrelated with mechanical properties of various surface layers [1-2]. At the same time, the positive influence of coldhardening, in particular on durability of mating surfaces, is valid only until a certain value of the initial coldhardening. If during the preliminary treatment of a mating surface the degree of plastic deformation exceeds a certain value specific for this metal, then a process of trenching starts that under increased load may lead to lamination of overhardened and embrittled zones [3].

To ensure the predefined surface quality parameters of an item, finishing stages of machining include so-called optimal cutting modes that provide not only minimal wear of the cutting tool, but also maximum value of fatigue life and surface tensile strength of the parts [4-8]. Operation of metal cutting equipment under the optimal condition of machining ensure regular profile of surface pattern, thus allowing obtaining minimal values of wear intensity in mating machine parts [9]. Thus, setting certain technological conditions of machining ensure the best values of several performance characteristics of machine parts at the same time.

2. Model and methods

Since 2016, alongside existing standards GOST 25142-82, GOST 2789-73, new standards GOST R ISO 4287-2014 and GOST R ISO 25178-2-2014 have been introduced in Russia that define regulated three-dimensional parameters of surface roughness. Besides, the rough surface may be represented as a Fourier space including parameters that characterize the machining process and tool geometry [10]. Due to that, the function of the basic profile of transversal roughness may be written down as an equation
(Certificate of state registration of software no. 2017614676), allowing calculating the coordinates of the mathematical model. Such an approach served as a foundation for developing a software solution for solving the surface roughness (Fig. 2).

The surface points of a part processed with lathe turning (Fig. 1), as well as plotting the spectrogram of the regularities in profile formation after lathe turning with sufficient accuracy and obtaining its parameters, was the temperature in the cutting zone. By varying the parameters of these equations, one may describe the longitudinal roughness may be represented with an algorithm of pseudo-random numbers based on Box-Muller transform that when reduced to a common normal distribution allows obtaining an equation [10]

\[
f_1(x) = \frac{1}{2\pi} \times \left[ \frac{1}{1 + \frac{1}{B} + \tan(\arctan(B - \gamma))} \right] \\
\times \left[ a_1 \frac{0.125}{b_1} + c_1 \rho_1 \frac{0.1}{a} \frac{0.43}{\alpha} \rho_1 \sin \frac{0.165}{\alpha} \right] \\
- 0.5 \tau_p \rho_0 \beta \\
\left( \frac{1 - \alpha_2 B^{1-b_2} (1 - \sin \gamma)^{-x}}{1 - \alpha_2 B^{1-b_2} (1 - \sin \gamma)^{-y}} \right) + \frac{\delta}{\rho_1} \sin \alpha (\cos \gamma + B \sin \gamma), \right. \times \cos \alpha \right] \\
\left\{ \begin{array}{l}
\arccos \left( 1 - \alpha_2 B^{1-b_2} (1 - \sin \gamma)^{-x} \right) \\
+ \frac{\delta}{\rho_1} \sin \alpha (\cos \gamma + B \sin \gamma) \end{array} \right.\right) \sin \left( \frac{\pi x}{S} \right).
\]  

(1)

where \( v \) is the cutting speed, m/s; \( t \) is the cutting depth, m; \( S \) is feed, mm/rev; \( x_j \) is the length of the section of the processed surface of the blank, mm; \( \tau_p \) is the plastic resistance of the material, Pa; \( \lambda \) and \( \lambda_p \) are conductivity factors of the processed and tool material respectively, W/(m·K); \( \theta \) is the fusing temperature of the processed material, °C; \( \alpha \) and \( \gamma \) are the clearance and face angles of the cutting tool, °; \( \phi \) and \( \phi_1 \) are the main and auxiliary angles in plan, °; \( r \) is the radius at the cutting tip in plan, m; \( \rho_1 \) is the rounding radius of the cutting edge of the cutting tool, m; \( \delta \) is the cutting tool wear along the back surface, m; \( a \) is thermometric conductivity of the processed material, m²/s; \( c_1 \) is the specific volumetric heat capacity of the processed material J/(m³·K); \( a_1 \) is the thickness of cut, m; \( b_1 \) is the width of cut, m; \( b \) is the total length of the cutting edges, m; \( \beta, \epsilon \) are cutting point and tool nose angles in plan, °; \( B = \frac{cB^x}{I^y (1 - \sin \gamma)^{0.73}} \) is a non-dimensional complex; \( B = \frac{\nu a_1}{\lambda} \) is a non-dimensional complex; \( I = \frac{\lambda_p}{\lambda} \frac{\beta \cdot \epsilon}{I} \) is a non-dimensional complex; \( \lambda = a/b_1 \) is a non-dimensional complex; \( a_2, b_2, c, x, y, z \) are factors depending on the properties of the processed and tool material and the geometry of the tool.

This equation may be used for calculations in the range of the cutting speeds from the highest build-up forming speed \( v_{bu} \) to the optimal \( v_0 \) at \( r \left[ 1 - \sqrt{1 - (S/2r)^2} \right] \leq t \leq r(1 - \cos \phi) \).

The longitudinal roughness may be represented with an algorithm of pseudo-random numbers based on Box-Muller transform that when reduced to a common normal distribution allows obtaining an equation [10]

\[
f_2(y) = \frac{4}{\pi} F(j, P_x, P_y, \phi, \phi_1, \theta, \rho_0, \lambda, \nu) \sin \left( \frac{y}{2R} \right) + \alpha \phi.
\]

(2)

where \( R \) is the radius of the processed blank, \( P_x \) and \( P_y \) are the components of the cutting force, \( \theta_p \) is the temperature in the cutting zone. By varying the parameters of these equations, one may describe the regularities in profile formation after lathe turning with sufficient accuracy and obtain its mathematical model. Such an approach served as a foundation for developing a software solution (Certificate of state registration of software no. 2017614676), allowing calculating the coordinates of the surface points of a part processed with lathe turning (Fig. 1), as well as plotting the spectrogram of the surface roughness (Fig. 2).
3. Computational modeling and experiment
Basing on the proposed methodology of the mathematical description of the profile, 3D models of surface after lathe turning were created and their interaction (contact) was modeled with the help of a Finite Element Method-based system. The profiles were modeled for various processing modes. In particular, Figure 3 shows a fragment of surface profile obtained by lathe turning at $v = 41$ m/min, $t = 0.5$ mm, $S = 0.2$ mm/rev made of 20Cr13 according to GOST 5632-72 with a hardness of 330HV.
The testing was conducted at a rubbing velocity of 0.08 m/s and a normal load of 9.81 N. The design model is shown in Figure 4.

**Figure 4.** A design model of contact interaction between the specimens for analysis with the Finite Element Method: $F$ is a normal force, $V$ is a rubbing speed, specimen 1 is still, specimen 2 is moving.

At the first stage of modeling, the contact interaction between two surface profiles, the number of contact areas was predicted and their locations as the profiles are closing (Figure 5).

**Figure 5.** Predicting the number of contact areas and their location as the profiles are closing

Then, a calculation was performed in accordance with the loading diagram shown in Figure 4, that resulted in obtaining the deformation distribution pattern when the profiles come into contact (Figures 6, 7).

**Figure 6.** Deformation distribution pattern at the moment of the first contact between the specimen profiles
From analysis of Figures 6 and 7, one may conclude that after the green run, the contact interaction pattern became more uniform. The number of areas with a pinpoint contact reduced, while the number of areas with a larger contact area increased (flat contact areas).

The experiments were conducted in the laboratory of the Department of Aircraft Engines and General Engineering, Rybinsk State Aviation Technical University named after P.A. Solovyov with the help of a T-11 friction machine. In the figure, you can see the photograph of the second specimen after the green run, as well as the results of modeling the run-in surface with the equations 1 and 2.

The experimental research has revealed a dependency (see Figure 9) of the equilibrium roughness parameter on the normal force of interaction between the specimens.
Figure 9. A dependency of equilibrium roughness on the normal force,

\[ R_{z_{eq}} = 8.15 \exp(0.19 \cdot F) \] (3)

Validity of the obtained data was evaluated with the Student's test at the probability value of 0.95.

4. Conclusion
Using the Finite Element Method has allowed finding the contact interaction area, the values of deformation and stresses in the contact zone, load distribution patterns along the surface, the value of contact closing and a number of other parameters.

The developed software solution allows calculating the longitudinal and transversal roughness of items produced with lathe turning according to GOST R ISO 4287-2014 and GOST R ISO 25178-2-2014, which are created on the basis of ISO 25000 international standard. It allows for fast import of data into any top-level CAD systems for subsequent plotting and analysis of a 3D rough surface.

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