Model of processing accuracy prediction with consideration of multi-stage process of circular grinding with axial feed

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Abstract. The article describes the solution of the problem of increasing the efficiency of a circular grinding with CNC by applying a model of processing accuracy prediction which considers the multi-stageness of the circular grinding process with axial feed during designing and optimization stages of control cycles for the radial and axial feeds. High productivity of external circular grinding operations with axial feed is ensured by simultaneous control of automatic stepwise cycles of radial and axial feeds in different sections of the shaft. Computed models have been developed; for given grinding cycles of radial and axial feed they allow to determine values of all main error types which are caused by the presence of initial radial run-out of the billet and elastic deformations of the technological system in three shaft sections (in reverse and non-reverse zones): diameter error, circularity deviation, radial run-out, cylindricity deviation, longitudinal section profile deviation, and total radial run-out.

1. Introduction
Circular grinding operations with axial feed EGAF performed on CNC machines are widely distributed in mechanical engineering. Requirements to increase productivity and short terms of circular grinding operations designing under conditions of mass production as well as high volume of necessary design work necessitated the automation of technological designing of operations using computer facilities, information technology and mathematical model of the designed processes. Nevertheless, many design tasks in engineering technology, including the task of calculating the optimal cycles of radial and axial feeds for CNC machines, still do not have a sufficiently complete and valid mathematical description due to the lack of appropriate analysis techniques [1-5,7-8,15,17]. In accordance with the development program of the digital economy in Russian Federation, modern engineering is faced with the task of creating multifunctional systems providing high accuracy, uniformity, quality, productivity, veracity of research results and reliability, stability of measurements in complex process of abrasive processing which impose different technological limitations on the permissible dimensions, machine and abrasive tool parameters [14,16].

In digital production technological preparation is conducted in a single virtual environment with using technologies of digital modelling and designing produce, products and production processes by creating digital twins of the product and technological processes of its production which are used simulate the production of produce throughout its life-cycle in the virtual model, which includes equipment, production process and enterprise personnel. Digital production involves through automation of technological preparation of the production, including full automation of control
program development processes for CNC machines by placement all information about operation under digital format and use of virtual modelling, which allows to identify possible problems, find optimal parameters of cutting modes, predict processing accuracy and check the reliability of the control program for CNC machine under varying conditions of processing a batch of the workpieces [6,9,11]. However, there are still no virtual environments and technologies of digital designing of control programs for CNC machines, including the calculation of optimal control cycles for radial and axial feeds considering technological constraints and unstable grinding conditions of workpieces batch for operations EGAF.

Calculation of the processing error is carried out on the basis of the obtained values of radius vectors for each of the considered sections. Each section is described by an array of radius vectors the current values of which are calculated during the whole processing cycle as described in the works [1,3,5,7,10-11,14].

2. Model of processing error prediction for given control cycles of radial and axial feeds

Our article presents a model processing error prediction, considering the main shape and location of the surfaces inherent in EGAF and external grinding with radial feed (EGRF):

• Diameter error (DR),
• Roundness deviation (RD),
• Radial run-out (RR),
• Cylindrical deviation (CD),
• Longitudinal section profile deviation (LSPD),
• full radial run-out (FRR).

It should be noted that the tolerances of shape and location of the surfaces are set more accurate then diametrical dimensions tolerances. Therefore, they have a decisive impact on the cycle productivity. Let us consider in more detail how each of processing error in EGAF is found. DR is the difference between the limiting values of an actual diameter, mm:

$$\delta_{DR} = D_{max}^{RZ1, RZ2, NZ} - D_{min}^{RZ1, RZ2, NZ},$$

where

$$D_{max}^{RZ1, RZ2, NZ}$$, $$D_{min}^{RZ1, RZ2, NZ}$$ — maximum (minimum) diameter value of section reverse zone in section1 (RZ1), non-reverse zone in section2 (NZ) and reverse zone in section3 (RZ2) on i-th stroke of z-th stage which is found as a sum of two differently directed radii lying on the one straight line, mm.

To calculate the radii (R) it is necessary to choose such section (RZ1, RZ2 or NZ) in the plane of which the radii have the greatest difference between them. R (mm) is the difference between maximum and minimum radius in this section:

$$\delta_{R} = R_{max}^{RZ1, RZ2, NZ} - R_{min}^{RZ1, RZ2, NZ},$$

where

$$R_{max}^{RZ1, RZ2, NZ}$$, $$R_{min}^{RZ1, RZ2, NZ}$$ — maximum (minimum) radius value in one of the sections (RZ1, RZ2 and NZ) on i-th stroke of z-th stage, mm.

Fig.1 shows the scheme for calculating RD about middle profile element — regular circle (MPE), located about real profile (RP) of the processed surface provided that a mean squared deviation of RP points from the MPE is minimum. MPE is the regular circle with a center at the point O, with coordinates h and w. RP has a center at the point O and can be described by an array of radius vectors on k-th number of billet radius on i-th stroke of z-th stage, mm.

RD for each section is found by the formula:

$$\delta_{RD} = R_{max}^{\text{max}} + R_{max}^{\text{min}},$$

where

$$R_{max}^{\text{max}}$$, $$R_{max}^{\text{min}}$$ — maximum (minimum) value of radius vectors RP in the MPE system is found by the formula:

$$R_{RZ1, RZ2, NZ}^{k} = \sqrt{(R_{k, i, z}^{RZ1, RZ2, NZ} \cos \beta - h)^{2} + (R_{k, i, z}^{RZ1, RZ2, NZ} \sin \beta - w)^{2}},$$

where
\[ h = \frac{2 \sum_{i} R_{Z1/Z2, Z}^{R} \cos \beta}{k_{\text{max}}} \cos \beta, \quad w = \frac{2 \sum_{i} R_{Z1/Z2, Z}^{R} \sin \beta}{k_{\text{max}}}. \]  

(5)

\[ \beta - \text{angle of radius about abscissa axis, deg; } k_{\text{max}} - \text{maximum number of considered radii.} \]

CD is found by the formula:

\[ \delta_{\text{CD}} = R_{Z1/Z2, Z}^{R_{\text{max}}} + R_{Z1/Z2, Z}^{R_{\text{min}}}, \]  

(6)

\( R_{Z1/Z2, Z}^{R_{\text{max}}}, R_{Z1/Z2, Z}^{R_{\text{min}}} - \text{maximum (minimum) value of radii located in different sections on k-th number of the billet radius on i-th stroke of z-th stage, mm.} \)

**Figure 1.** RD calculation scheme at EGAF

According to GOST R 53442-2009, LSPD — is the greatest distance from points on a real surface, which lie in a plane passing through its axis to the corresponding side of the adjoined profile within the normalized area. Table 1 presents formulas for calculating LSPD [18].

| LSPD type                     | LSPD formation condition | Formula for calculating LSPD |
|-------------------------------|--------------------------|-----------------------------|
| Cone shape (right cone)       | \( R_{Z1/Z2, Z}^{R_{Z1/Z2}} < R_{Z1/Z2, Z}^{R_{Z1/Z2}} < R_{Z1/Z2, Z}^{R_{Z1/Z2}} \) | \( \delta_{\text{LSPD}} = R_{Z1/Z2, Z}^{R_{Z1/Z2}} - R_{Z1/Z2, Z}^{R_{Z1/Z2}} \) |
| Cone shape (inverse cone)     | \( R_{Z1/Z2, Z}^{R_{Z1/Z2}} < R_{Z1/Z2, Z}^{R_{Z1/Z2}} < R_{Z1/Z2, Z}^{R_{Z1/Z2}} \) | \( \delta_{\text{LSPD}} = R_{Z1/Z2, Z}^{R_{Z1/Z2}} - R_{Z1/Z2, Z}^{R_{Z1/Z2}} \) |
| Saddle shape                  | \( R_{Z1/Z2, Z}^{R_{Z1/Z2}} < R_{Z1/Z2, Z}^{R_{Z1/Z2}} \) | \( \delta_{\text{LSPD}} = R_{Z1/Z2, Z}^{R_{Z1/Z2}} - R_{Z1/Z2, Z}^{R_{Z1/Z2}} \) |

Obtained values of processing error indices, calculated by formulas (1-6), are compared with corresponding permissible values indicated on the workpiece drawing. As a result of the fact that the current values of the radii on i-th stroke of z-th stage are known, it becomes possible to calculate the
accuracy limits. Therefore, in order to predict the processing accuracy for a given cycle and grinding conditions, a model of the error in shape and location of the processed surface along the whole processing length has been developed (Fig 2).

![Figure 2. Modeling restrictions on the permissible error of the processed surface size](image)

3. Conclusions
1. Processing accuracy model is designed for the cycles of circular grinding with axial feed on CNC machines with joint control of radial and axial feeds;
2. Based on the accuracy model, it’s possible to predict the processing error for given control cycles of radial and axial feeds through the diametric size, deviations of shape and location of the surface;
3. Allows to calculate the current values of actual radial feed, cutting force, radius of the section of processed hole surface, etc. for given cycles and various technological conditions of the grinding operation;
4. Model of processing accuracy is developed on the basis of surface shaping model; it is analytical and wide-range in varying technological factors because it is obtained on the basis of mathematical interrelation between processed surface radii, actual feeds and analytical model of cutting force, developed on the basis of the fundamental regularities of cutting process mechanics and theory of the plastic deformation of the metal in the cutting zone and establishing the connection with the main technological factors.

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