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Ensuring hole shape accuracy in finish machining using boring

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ABSTRACT

Introduction. In modern manufacturing, hole processing is one of the more labor-intensive operations. The presence of a large number of body parts with high-precision holes, which are subject stringent accuracy requirements regarding parameters such as size, shape and axis location, contributes to the complexity of their machining. Achieving these accuracy specifications often requires a diverse range of tools and multipurpose machining. Currently, there are numerous methods for hole processing, and boring is a key one for achieving high levels of accuracy. However, despite the many advantages of this method in achieving diametrical size accuracy, the shape deviation of the resulting holes has not been sufficiently investigated. **The subject.** The paper analyzes the main technological parameters of the hole boring process, and establishes their relationship with hole shape indicators, such as deviation from roundness and cylindricity. The study includes the development of an approach to predict error magnitude, considering the kinematics and dynamics of the machining process. **The purpose of the work** is to predict the radial displacement of the tool axis and to develop methods for ensuring the accuracy of the hole shape in finishing operations using boring. The main tasks of the present study involve establishing dependencies between technological processing parameters and the values of deviations from roundness and cylindricity, as well as determining the magnitude of the radial displacement of the tool to enable error magnitude prediction. **Method and methodology.** Methods for measuring deviations from roundness and cylindricity are considered, and their advantages and disadvantages are presented. Special attention is given to determining the influence of key factors during machining using frequency analysis method, which allows for evaluation the quality and reliability of the measurements performed. The hardware used for the experimental studies, along with the selected materials and processing modes, is described. **Results and discussion.** This paper examines the main factors affecting the accuracy of the hole shape obtained by boring. The application of the developed algorithms and models enables engineers to select optimal processing parameters based on the specified functional accuracy requirements of the hole, thereby ensuring the required shape accuracy.

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Introduction

Hole machining is one of the most labor-intensive operations in the production of mechanical parts on *CNC* machining centers. The high labor intensity is not due to the number of holes, but rather to the manufacturing accuracy requirements. This is related to their functional purpose, as holes are most often used as the main surfaces for installing shafts, axles, bearings, etc.

In general, the parameters of hole accuracy include the accuracy of the diameter size, the accuracy of the shape, and the location of the axis. The accuracy of the geometric shape refers to macrodeviations and, when processing holes, is usually regulated by deviations from roundness and cylindricity. In practice, shape tolerances for holes are most often assigned based on the size tolerance in the ratio of 0.25 to 0.5 IT.

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The most frequently used machining methods for high-precision holes in finishing operations are reaming and boring. The boring operation is widely used in modern mechanical engineering. Boring tools can be multi-blade or single-blade. Multi-blade tools are most often used for rough machining of holes, while single-blade boring tools are applied in finishing and fine boring operations.

Boring tools are adjusted to the size being performed, which is their main advantage. However, in practice, the boring operation is highly labor-intensive due to the need for adjustment to the required size [1–4]. It is necessary to use multi-pass processing with preliminary adjustment of the cutter, subsequent measurement, and repeated passes. This issue is minimized by automated systems for adjusting the boring head to the processing size within the machining center using measuring systems.

The boring method allows achieving high precision parameters in terms of diametrical size as well as axis location [1, 5], in comparison to tools such as reamers, countersinks, and holes obtained using the milling method [6]. This is directly related to the cutting forces arising during processing, which are significantly lower with the finish boring method.

However, the authors in [5] note the presence of elastic deformations (radial displacement of the boring cutter) and highlight the importance of this factor when boring deep holes. The paper proposes usng a semi-analytical dynamic method to determine the magnitude of elastic deformations of a boring tool. In the works of the authors [7–9], various approaches to dynamic systems describing elastic deformations of boring tools during processing are investigated.

Also, in [1], to eliminate elastic deformations of the boring tool during machining, the use of built-in strain gauges in the boring tool was investigated. According to the study, these sensors measure the bending of the boring cutter in real time. Strain data is transmitted to the *CNC* system of the machine through a programmable logic controller. Based on this data, the system automatically compensates for bending by adding a corrective offset along the coordinate axes of the machine. The authors also note that the developed system allows for a significant reduction in the error of the diameter size of the hole, especially at small cutting depths.

Some authors [10] consider an online monitoring system [11] for boring operations. They propose a methodology for effective online monitoring of tool conditions, which includes the use of adaptive neuro-fuzzy inference systems (*ANFIS*) for measuring the degree of wear and artificial neural networks (*BPN* — back propagation neural network) for classifying tool condition. This approach allows the boring process to be stopped timely when the wear threshold is reached, ensuring accuracy and preventing defects. The operation of artificial neural networks and neuro-fuzzy inference systems is based on the registration of cutting force signals (tangential, longitudinal, and radial) obtained from piezoelectric dynamometers.

Some research teams are working on developing and optimizing the designs of boring tools. For instance, the authors [12] proposed a new device for ultrasonic elliptical vibration boring. The research results showed that this device effectively reduces vibrations during processing and helps improve the quality of the machined surface. The authors [13] investigated the vibration stability of the boring process using dynamic vibration absorbers (*DVA*). The study demonstrated that using dynamic vibration absorbers with optimal damping and rigidity parameters significantly reduces the vibration amplitude of the boring cutter.

The main accuracy parameter achieved in the considered works was the diametrical size of the obtained holes. These works also addressed issues related to ensuring the form accuracy (deviations from roundness and cylindricity). Currently, measurement of hole form deviations is performed in accordance with international standards regulating the main evaluation methods — *ISO 12181–1:2011* and *ISO 4291:1985*, namely [14, 15]:

Least squares circle (*LSC*);

Minimum circumscribed circle (*MCC*);

Maximum inscribed circle (*MIC*);

Minimum zone circle (*MZC*).

The authors [18] described mathematical models for each of these methods and conducted experiments to evaluate their effectiveness. Based on the results, they proposed an improved assessment algorithm that reduces measurement error when using the *MZC* method.

Paper [19] presents a new method for estimating deviation from roundness based on an improved bat algorithm (*BA*). This method is based on the least gap approach and transforms the roundness deviation estimation into an optimization problem, where the goal is to find the optimal circle center. The authors highlight the high accuracy and efficiency of this method compared to traditional approaches.

Paper [20] studies the use of morphological filters for functional evaluation of part profiles and compares them with the well-known *2RC* and *Gauss* filters. The authors propose using mathematical morphology methods based on the theory of alpha shapes in combination with the *Gauss* filter to better determine the tribological characteristics of part surfaces.

The studies considered aim to increase accuracy and optimize the measurement process, which is crucial for achieving high functional characteristics of manufactured parts.

Based on the analysis of modern research, it can be concluded that most work focuses on ensuring the accuracy of diametrical size using the boring method. However, it is also important to address the accuracy of the shape. Therefore, ***the purpose of this work*** is to predict the radial displacement of the tool axis and to develop methods for ensuring the accuracy of hole shapes obtained during finishing by boring.

The following tasks are set in this work:

1. Determine the relationship between deviations from roundness and cylindricity of machined holes and the technological parameters of mechanical processing.
2. Determine the magnitude of the radial displacement of the boring tool by developing a mathematical model capable of predicting the error magnitude in the resulting holes.
3. Develop a method for assigning machining passes that accounts for axis deviation of holes at roughing stages and radial displacements of the finishing tool, considering the influence of allowance size and unevenness.

Methods

The studies were conducted on milling machining centers from *DMG MORI* equipped with the *Heidenhain TNC 620 CNC* system (Germany): a three-coordinate model – *DMC 635 V ecoline*, and a five-coordinate model – *DMU 50 ecoline*. The positioning accuracy along the *x*, *y*, and *z* axes of the machining centers' executive components is 8 μm. The maximum spindle speed is 8000 min^{-1}, and the maximum feed rate is 24 m/min.

The cutting tool was controlled and measured using a *Heidenhain* model *TT140* optical contact sensor. A *Heidenhain* model *TS 640* measuring probe was used to measure the diameter dimensions and the coordinates of the centers of the machined holes in three different sections.

Measurements of deviations from roundness and cylindricity of the processed holes were carried out using the *Roundcom–41C* instrument. In this work, the method of the largest inscribed circle (*MIC*) was chosen to evaluate deviations from roundness [18]. The main factors influencing the formation of deviations from roundness were determined using harmonic analysis [16, 17]. Fig. 1 shows spectrograms of the decomposition coefficients obtained when measuring the part on the roundness meter.

The materials selected for processing in this work were:

– aluminum alloy *EN AW-2024* (*Al-Cu-Mg alloy*), widely used in aircraft and automobile manufacturing due to its physical and mechanical properties;

– structural steel *AISI 5140* (*0.4 C-Cr*), which has a wide range of applications in mechanical engineering.

Preliminary hole processing was performed by drilling using a drill from *Sandvik Coromant* (*DIN 1899*) *R840–1400–30–A1A 1220*. The diameter accuracy corresponded to the eighth quality grade.

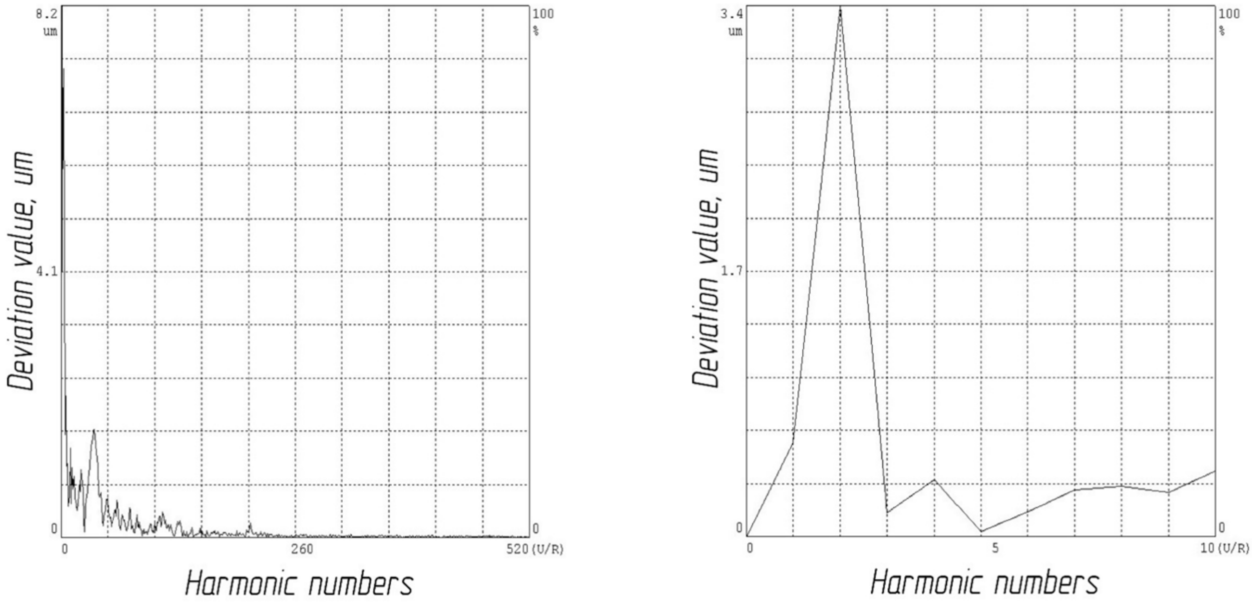
The processing conditions were as follows:

– for aluminum alloy blanks: feed per revolution ($\boldsymbol{F_u}$ = 0.05; 0.075; 0.1) mm/rev, rotational speed ($\boldsymbol{n}$ = 800) min^{-1}.

– for steel blanks: feed per revolution ($\boldsymbol{F_u}$ = 0.05; 0.075; 0.1) mm/rev, rotational speed ($\boldsymbol{n}$ = 100) min^{-1}.

The processing depth ($\boldsymbol{b}$) was 20 mm. The tool extension length was 179.691 mm, with the boring cutter extending 70 mm from the boring bar. The diameter of the holes processed ranged from 14 to 17 mm.

For machining, a boring bar *C5–391.37A–16 070 A* and a carbide boring cutter *R429U–E16–11066TC06* from *Sandvik Coromant* were used.



a *b*

Fig. 1. Spectrograms of the decomposition coefficients in:
a – the scale of all recorded harmonics; *b* – the range from 0 to 10 harmonics

Results and discussion

The workpieces were processed on two machining centers with different actuator layouts. Cutting modes were selected based on the requirements for the quality and accuracy of the surfaces being processed, as well as the tool manufacturer's recommendations.

However, when machining structural steel blanks, the selection of cutting modes was iterative. The initially recommended processing modes caused high vibrations and poor surface quality (see Fig. 2). Increasing the cutting speed (***V***) to 84 m/min resulted in breakage of the cutting plate. Conversely, reducing the cutting speed (***V***) to 3 m/min allowed achieving the required surface quality and accuracy without vibrations during machining.

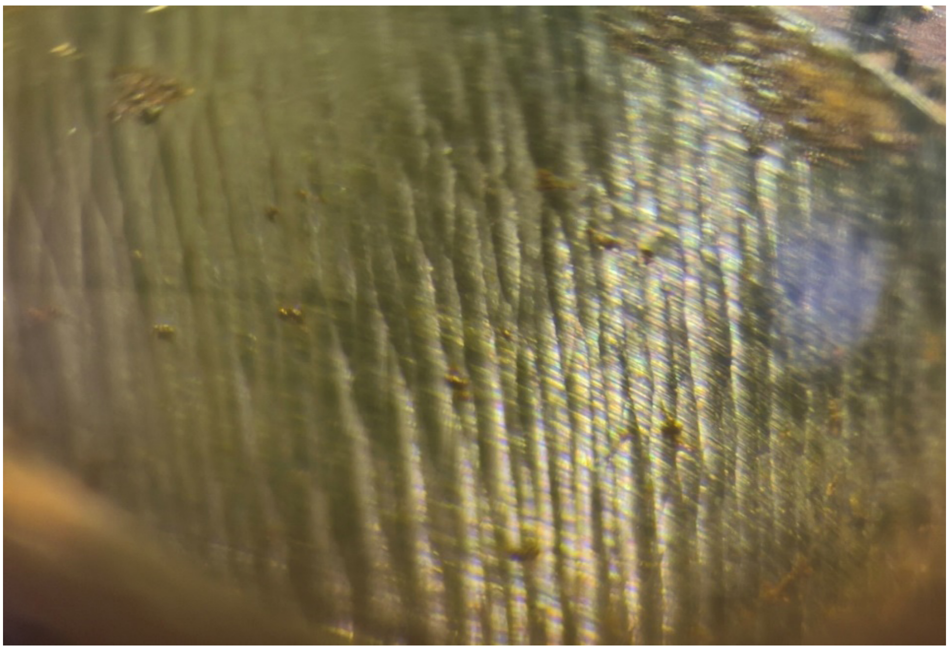


*Fig. 2.*Photograph of the hole surface obtained as a result of vibrations that occur during processing

This observation indicates that the cutting speed depends on the length of the boring tool for ensuring vibration-free processing. Nevertheless, it should be noted that reducing the cutting speed negatively affected productivity: the duration of the machining increased by 1.5 times.

The results of the experiments are presented in Figs. 3 and 4. Analysis of these data shows that as the feed rate increases, the deviations from roundness and cylindricity also increase. This trend holds true for both aluminum alloy and structural steel workpieces.

Additionally, machining on different centers exhibited some differences. Machining aluminum workpieces on the *DMU 50 ecoline* center resulted in lower deviations from roundness and cylindricity compared to the results obtained on the *DMC 635 V ecoline*.

The resulting holes were measured to assess the accuracy of the diametrical size and to determine the accuracy of the axis positioning. Measurements were taken in three sections, uniformly distributed along the entire length of the hole, using a measuring probe.

The results of the axis positioning accuracy assessment using the boring method, regardless of the feed rate, fall within the following limits:

– for the *DMU 50 ecoline* machining center – 13 μm in diametrical terms.

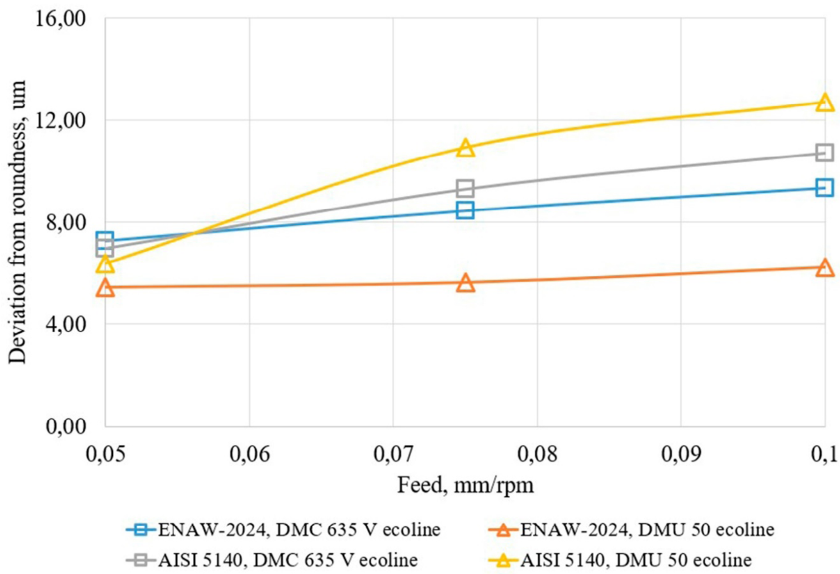


Fig. 3. Graph of the dependence of deviation from roundness on feed rate per revolution

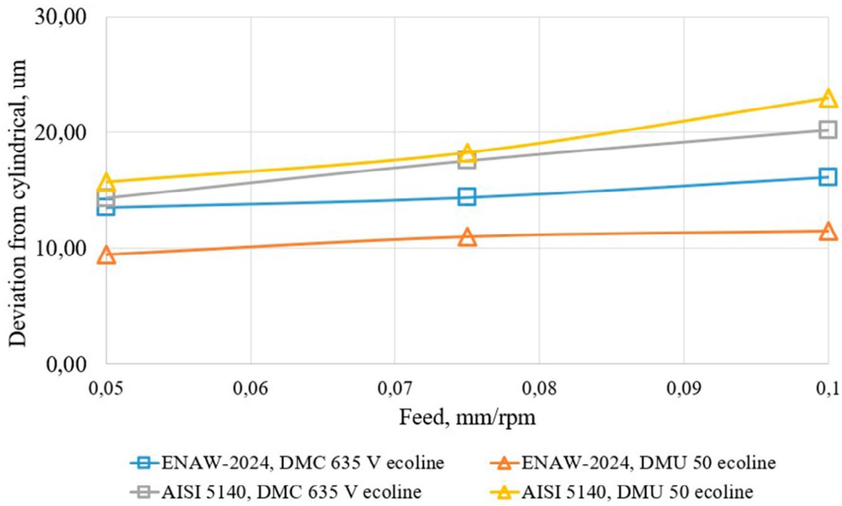


Fig. 4. Graph of the dependence of the deviation from cylindricity on feed rate per revolution

– for the *DMC 635 V ecoline* machining center – 5 μm in diametrical terms.

These results confirm the high degree of axis positioning accuracy achievable with the boring method [1, 5].

Special attention should be paid to the parameter of deviation from cylindricity. During measurements, a "conical" shape of the obtained holes was observed (Fig. 5). This phenomenon is associated with the radial displacement of the tool during machining and is directly related to the unevenness of the allowance.

Radial offset has a significant effect on the diametrical size of the hole and, in combination with uneven allowance, influences the deviation from the cylindrical shape of the resulting holes. Even with small deviations from roundness in different sections along the hole's length, a decrease in the diametrical size is observed.

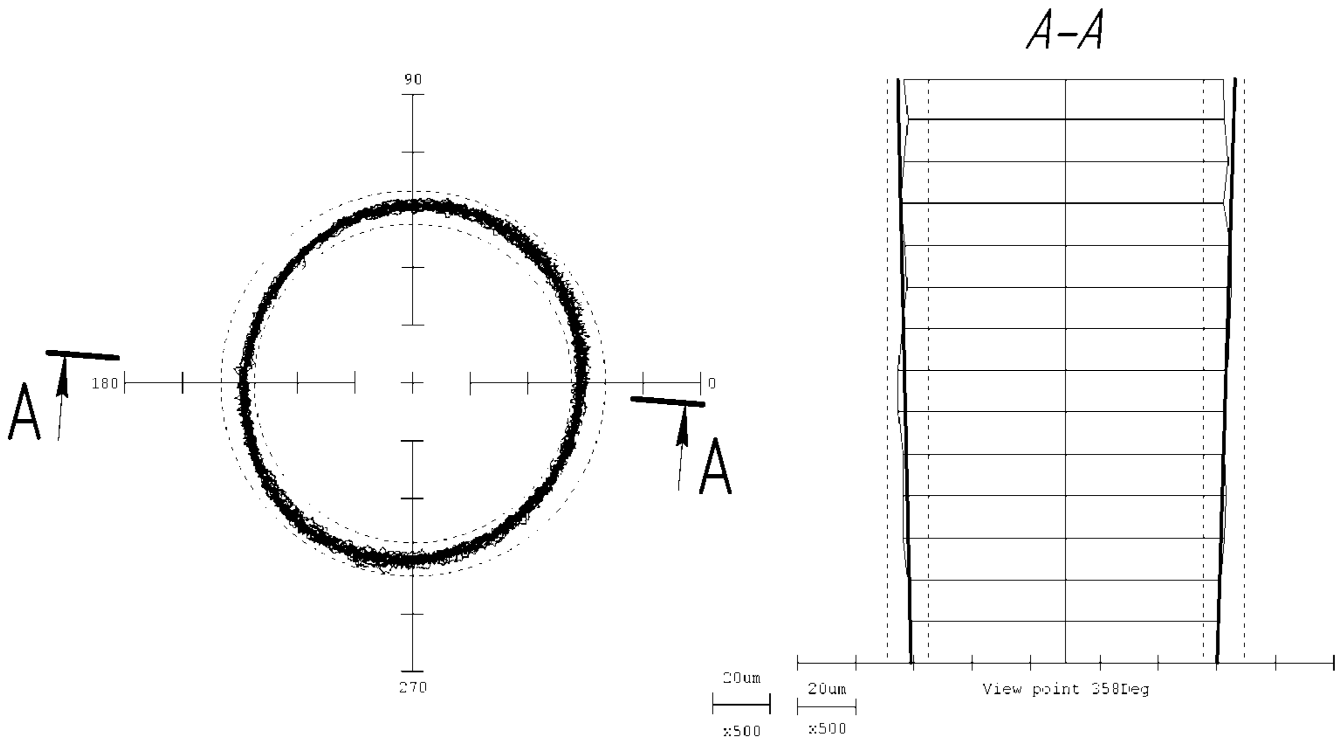


Fig. 5. Deviation from cylindricity along the hole length

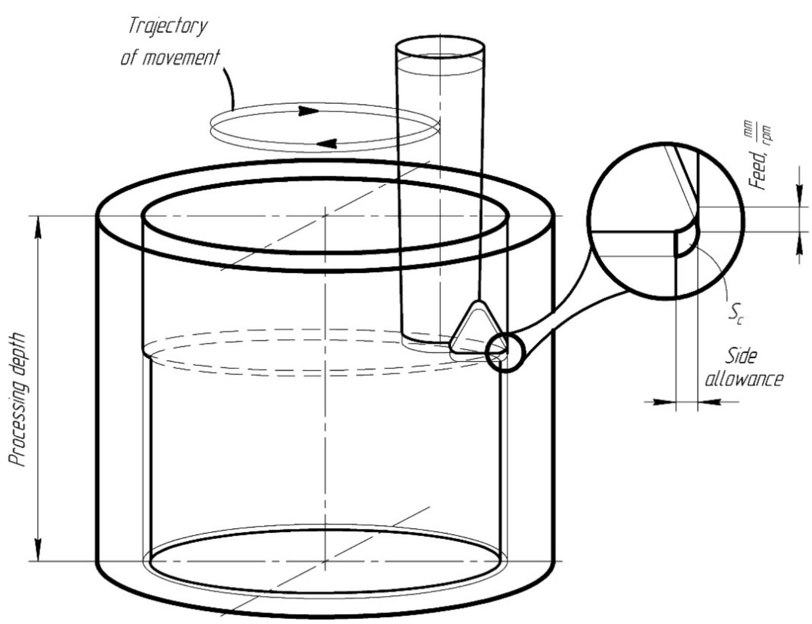


Fig. 6. Kinematics of the boring process

Therefore, by calculating the value of the radial displacement of the boring cutter, it is possible to:

– predict the error magnitude in the diametrical size of the hole;

– estimate the deviation from cylindricity in cases of allowance unevenness.

To analyze this, let us turn to the kinematics and dynamics of the finishing boring process (Fig. 6).

In the studied case, the kinematics of the cutting process is characterized as follows:

– the boring tool performs mechanical processing by removing chips;

– the quantitative parameters of the main and auxiliary movements are the rotation speed and feed;

– the combined movement of the tool, resulting from translational and rotational motions, forms a helical line;

– the pitch of the helix corresponds to the feed per revolution (expressed in mm/rev).

During material removal with a boring cutter, a cutting force arises. When this force acts in the radial direction, it causes displacement of the boring cutter.

To determine the bending component, we use the formula for calculating the cutting force from the theory of cutting [21]:

$$P = b \cdot s \cdot P_c,$$

where $\boldsymbol{b}$ is the processing depth; $\boldsymbol{s}$ is the thickness of the cut layer; $\boldsymbol{P_c}$ is the specific cutting force.

The product of the depth ($\boldsymbol{b}$) and the thickness ($\boldsymbol{s}$) gives the geometric area of the cut layer ($\boldsymbol{S_c}$).

Taking into account the kinematics of the cutting process, the region *abcd* characterizes the area of the cut layer $\boldsymbol{S_c}$ during the movement of the boring cutter in finishing boring of the hole (Fig. 7).

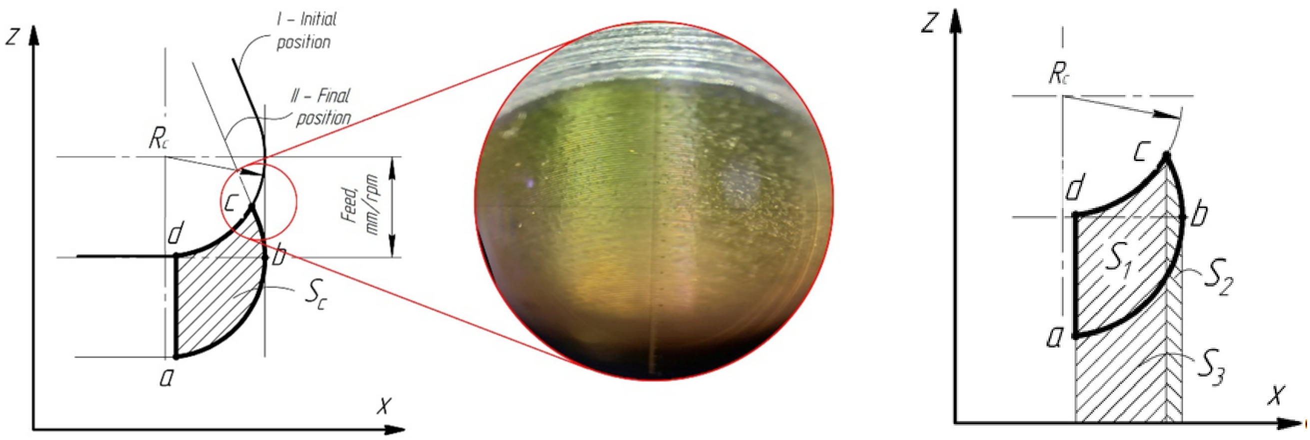


Fig. 7. Determining the area of the layer to be removed

The shape of the area *abcd* is formed by orienting the tool from the initial position *I* to the final position *II*, during one revolution with a displacement along the *z*-axis. As shown in the figure, the shape is formed by the intersection of two circles, which represent the radius of curvature of the cutting insert (R_{pl}). Thus, it can be concluded that this area is formed by a single circular function ($y = f(x)$), but at different moments in time.

The area of the formed region *abcd*, according to Fig. 7, will be found as follows:

$$S_c = S_1 + S_2 - S_3, \quad (1)$$

where $\boldsymbol{S_1}$ is the area under the circular function describing the geometry of the cutting insert within the range from point $\boldsymbol{c}$ to $\boldsymbol{d}$, mm²; $\boldsymbol{S_2}$ is the area under the circular function describing the geometry of the cutting insert within the range from point $\boldsymbol{b}$ to $\boldsymbol{c}$, mm²; $\boldsymbol{S_3}$ is the area under the circular function describing the geometry of the cutting insert within the range from point $\boldsymbol{a}$ to $\boldsymbol{b}$, mm²; $\boldsymbol{S_c}$ is the area of the cut layer of material, depending on the feed per revolution, mm².

The selection of the limits of the region *abcd* for calculating the area of the cut layer is directly related to the quadrants of the circle within which the given function $y = f(x)$ is defined.

Thus, taking into account the equation describing the circular function, we obtain:

$$S_c = \int_c^d y_0 - \sqrt{R_c^2 + (x - x_0)^2} + \int_b^c y_0^{II} + \sqrt{R_c^2 + \left(x - x_0^{\mathrm{II}}\right)^2} - \int_a^b y_0^{II} - \sqrt{R_c^2 + \left(x - x_0^{\mathrm{II}}\right)^2}, \quad (2)$$

where $\boldsymbol{x_0}$ and $\boldsymbol{y_0}$ are the coordinates of the center of the rounding radius of the plate in the initial position *I*; $\boldsymbol{x_0^{II}}$ and $\boldsymbol{y_0^{II}}$ are the coordinates of the center of the rounding radius of the plate in the final position.

By transforming the integrands using the integration by parts method, we obtain:

$$S_c = \left(y_0 \cdot x - \frac{1}{2}\left(\left(x - x_0\right)\sqrt{R_c^2 + (x - x_0)^2} - R_c^2 \arcsin\left(\frac{x - x_0}{R_c}\right)\right)\right)\Bigg|_c^d +$$

$$+ y_0^{\mathrm{II}} \cdot x \Big|_b^c + \frac{1}{2}\left(\left(x - x_0^{\mathrm{II}}\right)\sqrt{R_c^2 + \left(x - x_0^{\mathrm{II}}\right)^2} - R_c^2 \arcsin\left(\frac{x - x_0^{\mathrm{II}}}{R_c}\right)\right)\Bigg|_b^c -$$

$$- y_0^{\mathrm{II}} \cdot x \Big|_a^b - \frac{1}{2}\left(\left(x - x_0^{\mathrm{II}}\right)\sqrt{R_c^2 + \left(x - x_0^{\mathrm{II}}\right)^2} - R_c^2 \arcsin\left(\frac{x - x_0^{\mathrm{II}}}{R_c}\right)\right)\Bigg|_a^b . \quad (2)$$

To optimize the calculations, the y-axis of the coordinate system should be drawn through the center of the rounding radius of the cutting plate, where the coordinates $\boldsymbol{x_0}$ and $\boldsymbol{x_0^{II}}$ will be equal to zero, and the difference between the coordinates $\boldsymbol{y_0}$ and $\boldsymbol{y_0^{II}}$ reflects the feed per revolution.

Thus, taking into account equation (1) and (2), the calculated values of cutting force for the studied samples are presented in Table.

Table 1

Technological parameters of the finishing boring process

F_u, mm/rpm	S_c, mm^2	P_c, N/mm^2 *AISI 5140 / ENAW-2024*	P, N *AISI 5140 / ENAW-2024*
0.05	0.004987	1500/700	7.4805/3.4909
0.075	0.007456	1500/700	11.184/5.2192
0.1	0.009896	1500/700	14.844/6.9272

By modeling the situation with the unevenness of the allowance based on the calculation formula for determining the area of the cut layer, we can conclude that unevenness of the allowance of 0.1 mm leads to an increase in cutting force by a factor of 2 compared to the nominal value for finishing and, as a consequence, to an increase in the magnitude of the error.

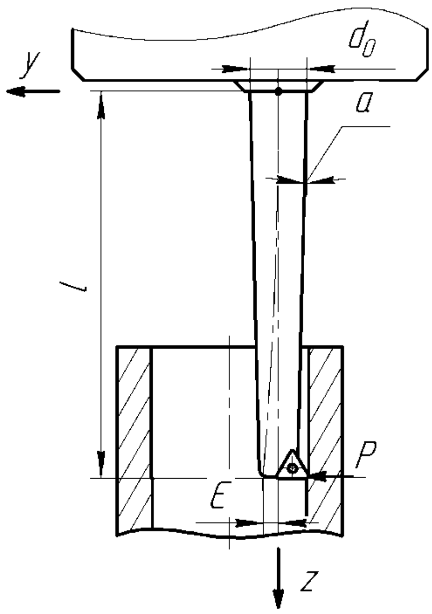


Fig. 8. Schematic of the boring process dynamics

Thus, at the stage of preliminary adjustment of the boring cutter, it is necessary to estimate the diametrical size of the hole along the entire length of the processing using a measuring probe. If deviations in the position of the hole axis center are detected in the range of 0.05 to 0.1 mm, it is recommended to perform a preliminary pass (semi-finished boring). This additional pass will eliminate the unevenness of the allowance exceeding the calculated values, taking into account the size and shape tolerance. This method allows minimizing the number of passes depending on the accuracy of the axis positioning at the previous pass.

The next step was to determine the magnitude of the radial displacement of the tool axis during fine boring of holes. At the moment the cutting tool cuts into the workpiece material, a cutting force begins to act on the boring bar in the contact zone. The tool holder, as shown in Fig. 8, is a conical surface with a cutting plate fixed to its end. This scheme is a system with variable stiffness with one degree of freedom, at the extreme point of which a cutting force (***P***) acts:

$$\begin{cases} \dfrac{d^2\varepsilon}{dz^2} = \dfrac{M_0}{EJ_x^0}; \\ M_0 = k(z) \cdot M(z) = \dfrac{J_x^0}{J_x(z)} \cdot M(z), \end{cases} \quad (3)$$

where $\boldsymbol{E}$ is the coordinate of the tool axis bending, mm; $\boldsymbol{z}$ is the tool length coordinate, mm; $\boldsymbol{M_0}$ is the reduced bending moment, N·mm^2; $\boldsymbol{J^0_x}$ is the moment of inertia of the boring bar at the origin of the coordinate system, mm^4; $\boldsymbol{k(z)}$ is the reduction factor; $\boldsymbol{M(z)}$ is the bending moment function; $\boldsymbol{J_x(z)}$ is the function of inertia moment.

The rigidity of this system changes according to the following relationship:

$$J_x(z) = \frac{\pi \cdot d(z)^4}{64} \rightarrow d(z) = d_0 - 2 \cdot z \cdot \mathrm{tg}\alpha,$$

where $\boldsymbol{d(z)}$ is the diameter change function; $\boldsymbol{d_0}$ is the diameter of the boring bar at the origin of the coordinate system, mm; $\boldsymbol{\alpha}$ is the angle of the conical surface of the boring bar, rad.

The solution to the system of equations (3) consists of reducing the system with variable rigidity to a system with constant rigidity. To do this, we will compose a differential equation describing the function of change in the reduced bending moment:

$$dM_0 = P \cdot \left(k(z)(l - z - dz) - l\right),$$

where l is the boring tool length, mm.

Taking into account that the reduction factor is found as the ratio of two moments of inertia in different sections, we obtain:

$$k(z) = \frac{J_x^0}{J_x(z)} = \frac{d_0^4}{(d_0 - 2z\,\mathrm{tg}\,\alpha)^4};$$

$$dM_0 = P\left(\left(\frac{d_0}{d_0 - 2z\,\mathrm{tg}\,\alpha}\right)^4 (l - z - dz) - l\right).$$

The solution of this differential equation by an analytical method will allow us to construct functions of reduced bending moments for each sample under study (Fig. 9).

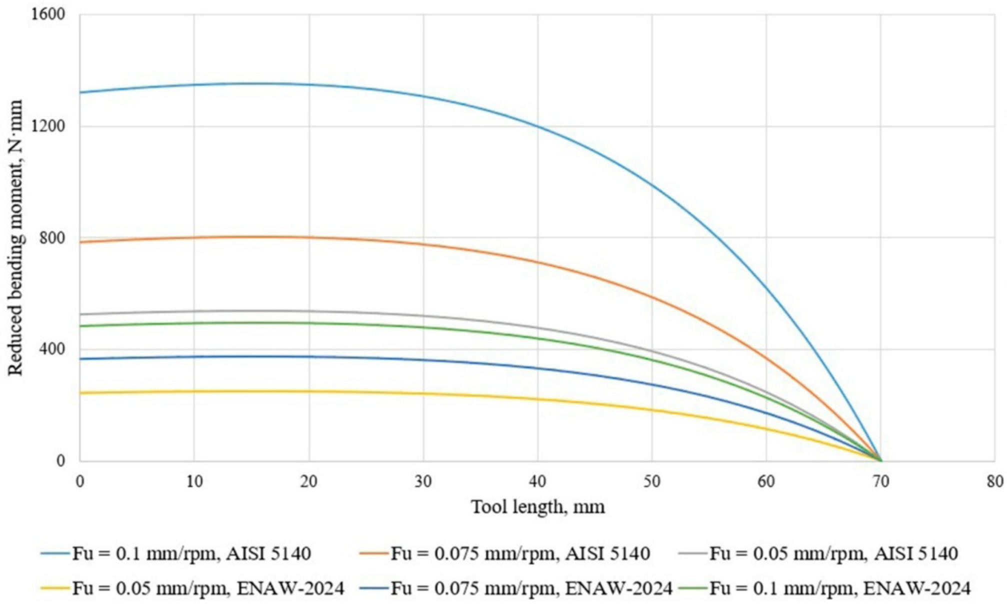


Fig. 9. Diagrams of reduced bending moments

Next, to find the radial displacement of the cutting tool at the maximum point, the *Mohr* integral method or the *Vereshchagin* method can be used [22].

Fig. 10 shows the dependence of the radial offset of the cutter on the feed per revolution. Analysis of the presented data allows us to conclude that the measured values of the maximum offset of the tool differ from the calculated ones by no more than 17 %. Thus, using the differential equation described above, it is possible to analytically calculate the radial displacement of the tool at the maximum point and numerically predict the magnitude of the error in the holes obtained during finish boring.

This paper examines the main factors influencing the accuracy of the shape of holes obtained by boring. The use of the developed algorithms and models enables the technologist to assign technological processing parameters depending on the accuracy specified by the service purpose.

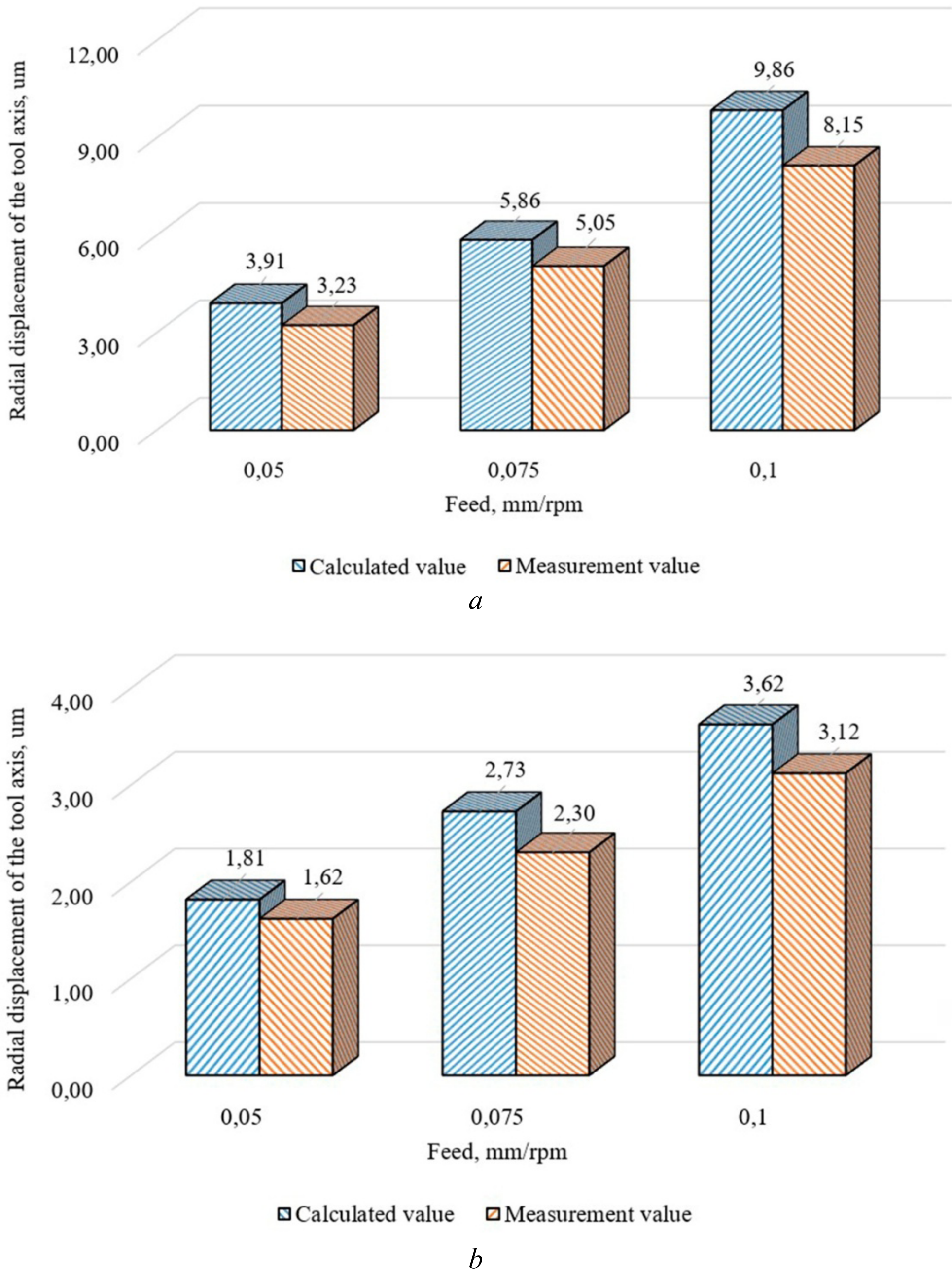


*Fig. 10.*Dependence of the radial displacement of the boring cutter axis on feed rateper revolution:

a – material: steel *0.4 C-Cr*; *b* – material:aluminum alloy*Al-Cu-Mg-Mn*(quenched and naturally aged aluminum alloy, containing ≤ 94.7 % *Al*; ≤ 4.9 % *Cu*; ≤1.8 % *Mg*; ≤ 0.9 % *Mn*)

Conclusion

1. The dependences of the deviation from roundness and cylindricality on the feed per revolution have been established; as the feed increases, the values of deviation from roundness and cylindricality also increase.

2. It has been shown that during fine boring, despite the small allowance, the rigidity of the boring cutter significantly contributes to the accuracy of the resulting holes, accounting for about 20–30 % of the tolerance value.

3. An algorithm has been developed to determine the area of the cut layer for finishing boring operations, taking into account the geometric parameters of the cutting tool and the technological processing parameters, enabling the calculation of the cutting force.

4. A model of the radial displacement process of the boring cutter has been developed. This model incorporates data on the technological parameters of the hole finishing process and allows determination of the radial displacement value of the boring cutter used in error calculation.

5. A method for assigning transitions has been developed that accounts for the deviation of the hole axis during roughing stages, the influence of the allowance value based on the developed mathematical models, including preliminary adjustment of the boring cutter and correction for the tool radius.

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Conflicts of Interest

The authors declare no conflict of interest.