792. Experimental studies of stabilization of boring cutter form – building top oscillation

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Abstract. The article deals with application of automatic control of cutting tool oscillations, which permits to control the cross-sectional form of a hole. This parameter can be controlled in mass-produced machine tools only through machine tool geometrical relationship, which is ensured during manufacturing of metal cutting machine tools. The purpose of the proposed control system is to increase technological capabilities of the equipment in order to improve boring accuracy as compared with the accuracy regulated by the standards for this type of equipment. Testing of the proposed technological equipment demonstrated high efficiency of damping in the process of boring in terms of response to mechanical and impact actions. Rational combinations of cutting modes were revealed, which provide the needed accuracy and acceptable productivity in the hole cutting process.

Keywords: automatic control system, oscillation stabilization, damping, boring, technological equipment.

1. Introduction

An automatic control system must ensure minimum amplitude of oscillations of a tool (due to elastic release) in the process of boring, which cause errors in the hole form and the surface location of its cross-section [1].

Theoretically in the absence of the machine tool geometrical errors and the constant cutting force (perturbation actions) $P = \text{const}$, the machining will be performed with the preset accuracy of the form and the surface location of the cross-section. In real conditions the system is affected by different factors causing the machining errors whose values change, for example cutting force is difficult to predict, and this, in its turn, leads to the necessity to consider tool form-building top deviation from the preset trajectory as a random value [2].

A usual technological scheme, from the point of view of automatic control, is an open system of controlling a sizing error, the surface location and form, which has no possibility to actively correct the values in the process of machining [3], i.e. the systems without a feedback.

2. Objects of research

From the technological point of view any system can be characterized by a specification factor K_{re}. Besides, the smaller is the ratio K_{re} which depends on various factors, but in the largest extent on the technological system rigidity, the higher is the quality of such system:

$$K_{re} = \Delta_{DET} / \Delta_{BAR}, \tag{1}$$

where Δ_{DET} is a part error; Δ_{BAR} is a blank error.

Due to the presence of some sections with low rigidity in the technological system, for example, a tool (when boring deep holes), whose significant increase is impossible because of objective reasons (in a large extent rigidity is limited by the hole diameter), the K_{re} value in an open system is limited, so, the accuracy achieved in machining is limited. When boring deep holes with a long boring bar, a dominating oscillating system is the tool system. Here the tool path makes up to 80 % and more in the technological system relative migration [4, 5].

The relations between the subsystems in the unified closed elastic system are performed through the cutting zone and can be replaced by the cutting force action. Let's represent the dominating oscillating boring system in the form of a continuous shaft loaded with the elastic force F_Y, resisting (damping) force F_C and the cutting force components P_Z and P_Y (Fig. 1).

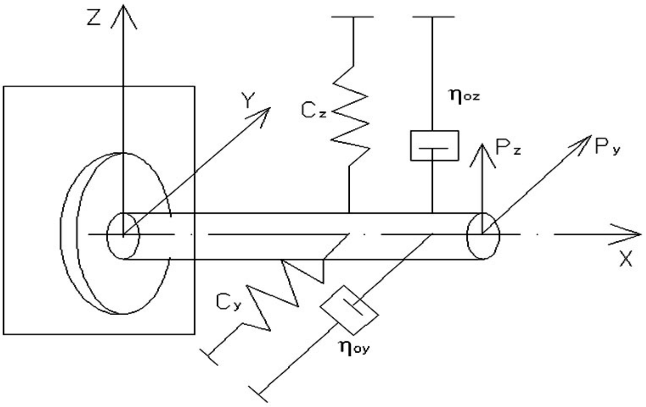

Fig. 1. Principal diagram of the dominating oscillating system in the process of boring: C_y, C_z are coefficients of rigidity of the generalized shaft along axis Y and Z, respectively; η_{oy}, η_{oz} are generalized resistance (damping) coefficients along the corresponding axis

3. Mathematical modeling of oscillating system when boring holes

Using the analytical expressions for the acting forces in *XOY* plane, the boring process can be described by the second order differential equation in the form [5]:

$$m\frac{\partial^2 y(t)}{\partial t^2}+\eta_0\frac{\partial\ y(t)}{\partial t}+C_y(t)=P_y. \tag{2}$$

The initial conditions have the form:

$$P_y=\begin{cases}KB[A_0a(t)^{y_p}+B],\text{when } a(t)>0,\\ 0,\text{when } a(t)\le 0,\end{cases} \tag{3}$$

where K, A_0, y_p are constants depending on the tool geometry and the properties of the material being machined; $a(t)$ is the thickness of the layer being cut; B is the width of layer being cut.

For the *YOZ* plane the mathematical model of the boring process for a console fixed part is written in the form:

$$\begin{cases}m\frac{\partial^2 z(t)}{\partial t^2}+\eta_{oz}\frac{\partial z(t)}{\partial t}+C_1(t)z(t)=P_z,\\ m\frac{\partial^2 y(t)}{\partial t^2}+\eta_{oy}\frac{\partial y(t)}{\partial t}+C_2(t)y(t)=P_y,\end{cases} \tag{4}$$

where the initial conditions for the *x* cutting force components are:

$$P_y = \begin{cases} KBa(t)^{y_p}, \text{when } a(t) > 0, \\ 0, \text{when } a(t) \le 0, \end{cases} \tag{5}$$

$$P_z = \begin{cases} KB[A_0 a(t)^{y_p} + B_0], \text{when } a(t) > 0, \\ 0, \text{when } a(t) \le 0. \end{cases} \tag{6}$$

Such a system operates in an open cycle and has no feedback for the active correction of elastic releases in the process of part machining. In other words, the essence of the open control principles consists in that the system control is based only on the preset algorithm of functioning and is controlled neither by the preset values nor by the value of perturbation actions (P_z and P_y).

If we introduce a feedback in the abovementioned system (4), operating on the principle of the open control, there will be realized the possibility to obtain information of the dynamics of the cutter top oscillation (perturbation action) by the angle of the blank turn, and by the results of these measurements to perform the control of the tool oscillation with the aim of stabilizing the cutter form-building top in the preset position independent on the perturbation action values changing.

The proposed technological equipment for stabilizing tool oscillations during machining (Fig. 2) as compared with the existing solutions [2, 3, 7] has a lot of advantages, namely, a more efficient and steady stabilization of the cutter form-building top, as it is known that the efficient control of oscillations can be ensured by the time constant of the system transient process (T_c) that is 5-10 times smaller than the period of oscillations (T_v) of the perturbation action. With such a ratio between T_c and T_v it is possible to damp efficiently the main low-frequency components of oscillations that characterize the form and location errors of the bored holes [8].

4. Experimental research of oscillations when boring holes

To do this in the unit (Fig. 2) there are introduced the following elements:

- a transducer for measuring elastic releases deviations of the boring cutter form – building top (pos. 7 in Fig. 2) strictly dependent on the cutting force (perturbation actions) changing;
- a transducer registering stimulus refining (pos. 8 in Fig. 2);
- a force mechanism (pos. 5 in Fig. 2) that refines stimulus (the tool oscillation damping in the process of boring).

As a result we obtain an automatic control system with principally new qualities. The casing of the unit for automatic control of the tool oscillations is fixed in cutter head 1 of the metal cutting machine tool and consists of: fixed part of the controlled equipment 2 and the controlled boring arbor with cutter 3 connected with each other through conical surface 4 with a threaded connection.

The fixed part 2 is installed with a cartridge made of a dielectric material, in which piezoelectric converter 5 (piezoengine) is located. It is manufactured of the sintered piezoelectric elements made of ceramics CTS-19.

The piezoengine has the following parameters: *L* is its length (230 mm); *D* is its diameter (20 mm); Δ*L* is the converter elongation ± 45 μm when changing the control voltage (± 400 V); *f* is the first natural frequency of the piezoelectric converter (10 kHz).

The fixed casing has a perpendicular protrusion with a threaded opening in which cartridge 6 is screwed, whose bottom is a fixed base for piezoelectric converter of path 5 (piezoengine). When the engine is mounted in the unit casing, to eliminate the gaps in the couplings with the support surfaces, there is performed a preliminary pulling. The piezoengine uses displacement sensors to measure elastic release deviations of the cutter form-building top (transducer 7) and to register the control action refining (transducer 8). Such a sensor is a condenser consisting of two plates, one of them is fixed, and the other is movable.

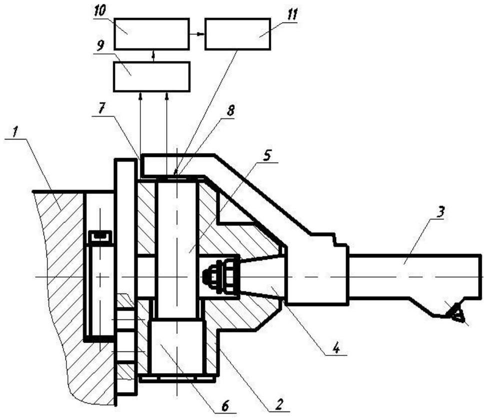

Fig. 2. Principal diagram of the unit for stabilization of the boring cutter form – building top: 1 – machine tool capstan head; 2 – controlled equipment fixed part; 3 – controlled equipment movable part; 4 – threaded conical fixation of the arbor; 5 – piezoelectric converter of the path (piezoengine); 6 – cartridge for piezoengine fixation; 7 – a transducer for measuring elastic releases deviations of the boring cutter form – building top; 8 – a transducer registering stimulus refining; 9 – prime amplifier; 10 – comparator unit; 11 – power amplifier

To evaluate the operation of the suggested unit there was carried out a series of experiments to define the system response to the voltage jump and to the mechanical impact perturbation with correcting elastic releases and without it. An experimental set for stabilization of the boring cutter form-building top is shown in Fig. 3.

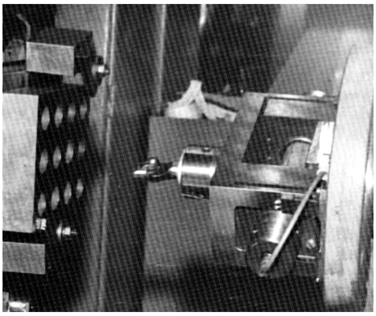

Fig. 3. Experimental setup for stabilization of the boring cutter form – building top oscillations

This gives us some information about the control time (response speed) and stability of the control action refining. First and foremost, let's check the unit response without correction of its dynamic characteristics (in the off state transducers 7, 8 and piezoengine 5, see Fig. 2). When the system is affected by a signal in the form of the voltage jump, the transient process (Fig. 4) is an oscillating and weakly-damped one. The graduating mark of the oscilloscope coordinate grid is 0,002 s along the abscissa (*T*, ms) and 1V (*U*, V) along the ordinate. The readjustment value is about 30 %, and the time of adjustment is 18 ms.

With such characteristics of the transient process the control system is not suitable for controlling the form accuracy and the hole cross-section location, as at oscillation frequency from 200 Hz to 600 Hz (the main harmonic oscillations of the hole form and location errors) [2, 6, 7] the time of one oscillation of the cutter form-building top makes from 5 to 1,6 ms, and the unit, without correction its dynamic properties (in the off state) has the control time of 18 ms, i.e. the system will not manage to respond to the speed of the tool elastic releases in the process of machining that takes the form of an oscillating process.

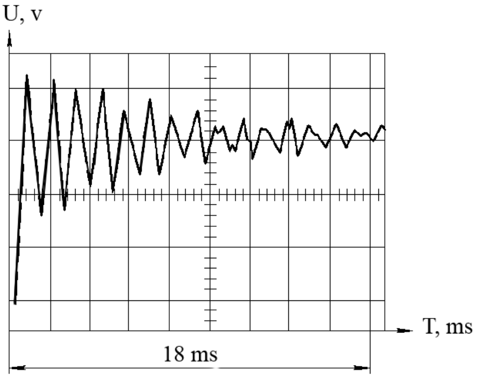

Fig. 4. System response to the voltage jump without correction of its dynamic properties

The system response to the signal that comes from the transducer of the tool position to the mechanical impact perturbation is shown in Fig. 5. The control time is more than 20 ms.

Now let's consider the unit response with correction of its dynamic properties by means of feedback circuit that will permit to improve significantly its characteristics. As the developed unit is the sixth order system and its optimal parameters adjustment coefficients calculation presents some difficulty, the system adjustment was performed by the form of the transient process be the way of selecting the integration factor K_u and the values of the coefficients that enter the correcting elements W_{K1} and W_{K2} [7]. The criterion of the automatic control system satisfactory adjustment was taken the minimum time of the adjustment with ensuring the system stability and the value of readjustment not more than 5 %.

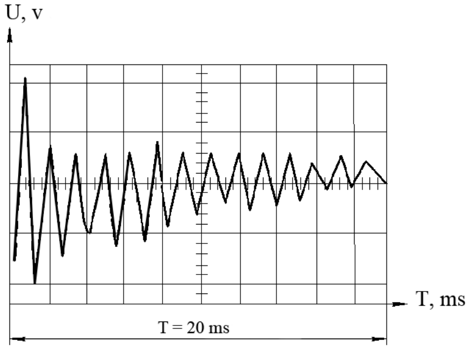

Fig. 5. System response without correction for the mechanical impact perturbation

As a result of introducing the correcting actions and their parameters selection, the time of the system adjustment with a perturbation action in the form of the voltage jump is reduced and the value of readjustment does not exceed 5 %. The transient process of the corrected automatic control system is shown in Fig. 6. The graduating mark of the oscilloscope coordinate grid along the abscissa is 0,5 ms (T, ms), along the ordinate - 1 V (U, V). The time of adjustment takes 0,8 ms with the control action refining which is 22 times less than in the system without correction of the cutter oscillation. The automatic control system response to the mechanical impact perturbation is shown in Fig. 7.

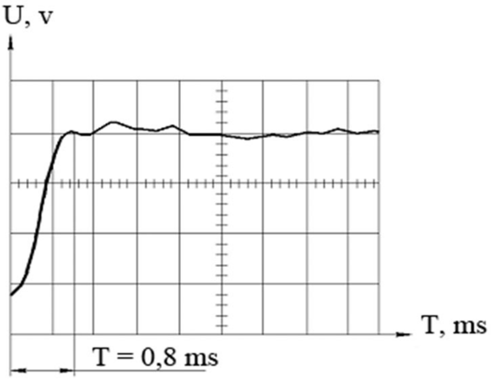

Fig. 6. System response with its dynamic properties correction for the voltage jump

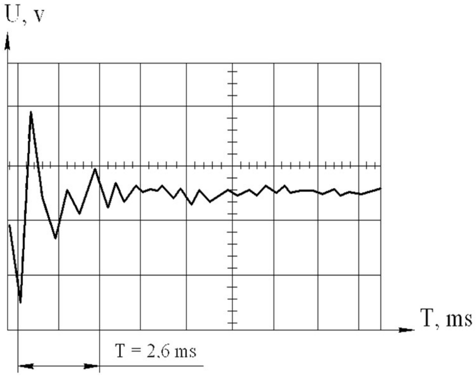

Fig. 7. System response with its dynamic properties correction for the mechanical impact perturbation

The graduating mark of the oscilloscope coordinate grid along the abscissa is 1 ms, along the ordinate - 1 V. The time of adjustment is 2,6 ms, which is 8 times less than in the system without correction.

The bench tests carried out showed that the natural frequency of the assembled unit is 1200 Hz. Its mechanical quality factor is ca. 30. The adjusted parameters of the automatic control system did not change in the process of carrying out experimental studies.

From the literature analysis it is known [3, 8, 10] that the cutting modes affect the achieved accuracy of machining. The revealing in the process of studying the suggested set (Fig. 3) technological possibilities of rational combinations of cutting modes would permit to assign the modes of machining that require the needed accuracy and acceptable productivity. Each of the factors (*V*, cutting speed; *S*, tool feed rate; *t*, cutting depth) can take any value within the limits of the selected range, so when assigning the limits of varying the factors, one is to take into account the following ideas:

- the value of the cutting depth is selected taking into consideration the range of changing *t*, used in semi-fine and fine boring of the studied diameter Ø30H7 ($^{+0,021}$) mm: t = 0,2 - 0,6 mm;
- selecting the range of changing feed rate is performed taking into account the parameter of the machined surface roughness: S = 0,05 - 0,2 mm/rev;

- the range of changing the cutting speed is selected based on the literature data and production observations. In accordance with work [3], when boring diameters from 18 to 30 mm the recommended range of the cutting speed is 0,43…1,60 m/s.

A series of single-factor experiments were performed in order to reveal the influence of these factors, to verify their varying ranges and their mutual effect. The results of these tests are summarized in Figs. 8-12.

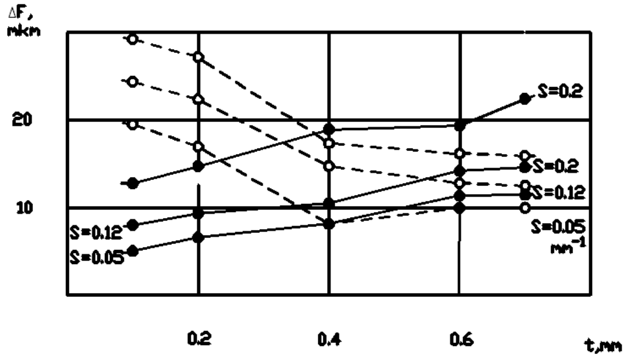

Fig. 8. Dependence of deviations from the cross-section roundness ΔF on the cutting depth t:

● with damping; ○ without damping

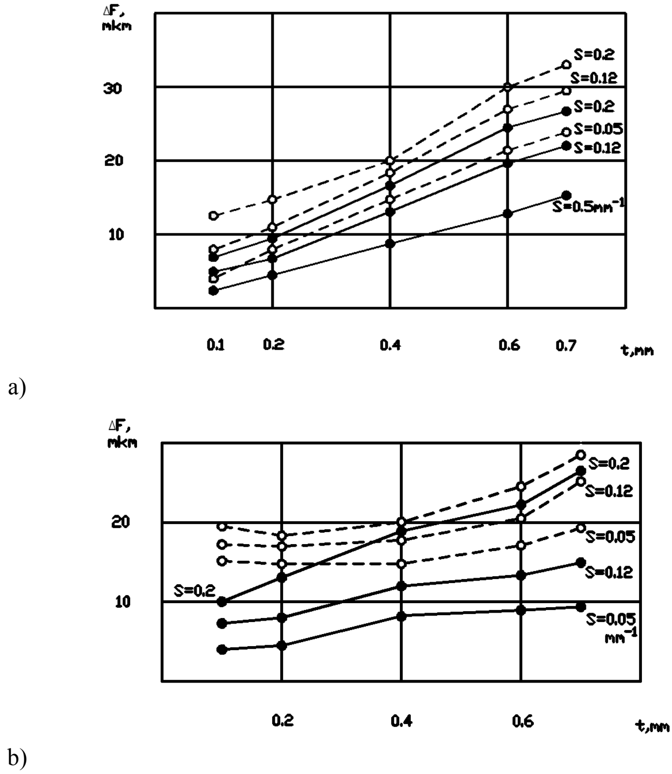

Fig. 9. Dependence of deviations from the cross-section roundness ΔF on the cutting depth t:
● with damping; ○ without damping; a) at V = 1,64 m/s; b) at V = 1,02 m/s

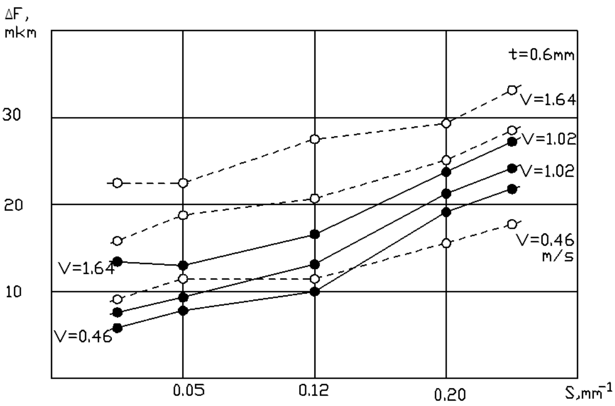

Fig. 10. Dependence of deviations of the cross-section roundness ΔF on the feed rate (t = 0.6 mm):
-●- with damping; -○- without damping

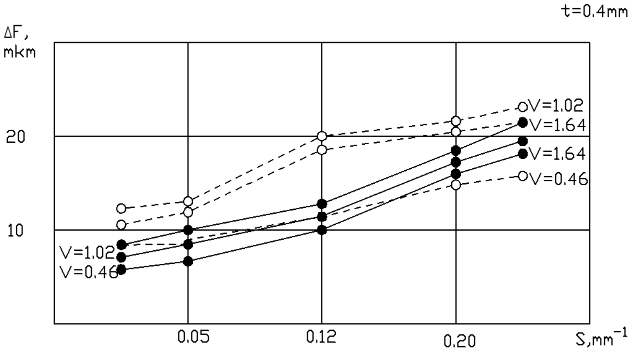

Fig. 11. Dependence of deviations of the cross-section roundness ΔF on the feed rate (t = 0.4 mm):
-●- with damping; -○- without damping

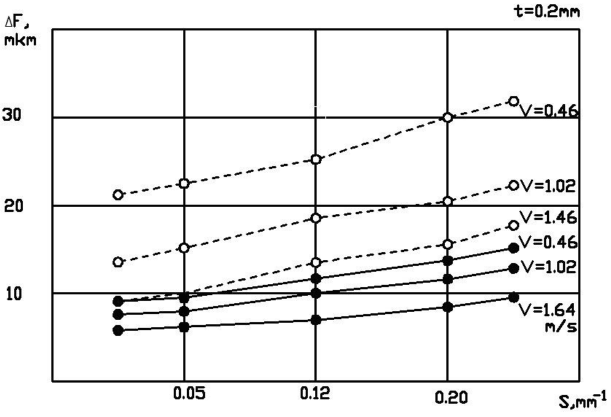

Fig. 12. Dependence of deviations of the cross-section roundness ΔF on the feed rate (t = 0.2 mm):
-●- with damping; -○- without damping

Plots in Figs. 8-12 demonstrate the effect of the cutting depth on the hole form accuracy. With the cutting speed V = 1,64 m/s and V = 1,02 m/s we observe the general reduction of the form error with lower cutting depth and feed rate. This is explained by the decrease of the tool elastic releases in connection with the reduced cutting force.

At the cutting speed $V = 0{,}46$ m/s we observe reduction of the form error with increasing the cutting depth, which is explained by the reduction of the share of the cutting depth random oscillations in the stock to be removed and, consequently, the cutting force within the limits of the spindle revolution has lower magnitude oscillations. However, with increasing the feed rate, the form error increases at all cutting depths.

Machining with the control system has the character of the form error dependence at $V = 0{,}46$ m/s equal to that at $V = 1{,}46$ m/s and $V = 1{,}02$ m/s. This is explained by the effect of the cutter top elastic migrations compensation for the variable cutting force.

Reducing the feed rate (Figs. 11-12) and the cutting depth leads to increasing the surface form accuracy due to decreasing the force action on the technological system. At the cutting depth $t = 0{,}2$ mm there is observed the increase of the form error with reducing the cutting speed when machining without damping, which is explained by the increase of the friction force on the cutter rear and by the instable cutting process.

Significant reduction of the form error ΔF with damping is observed in all the machining modes in the selected range.

Conclusions

1. The error of the hole location and form of its cross-section is conditioned by the effect of elementary errors whose value changes within the period of the blank revolution. The largest effect on the error in the location and form is caused by the tool (boring arbor) oscillation caused by the cutting depth, instability of mechanical properties of blank material and by variable rigidity of the technological system in various sections.
2. To stabilize efficiently tool oscillations, the time of the automatic control system adjustment must be within the limits of $T = 5\ldots1{,}6$ ms (the range of the main harmonic oscillations forming the machined surface form and location error). With such characteristics of the transient process the control system will manage to respond to the rate of changing tool oscillation in the process of machining.
3. The needed response for stabilizing oscillations in the developed automatic control system is ensured by using piezoelectric converters of displacement with corrected dynamic properties. Besides, the developed system has the time of adjustment $T_{re} = 0{,}8$ ms and the pass band $f = 0\ldots1200$ Hz.
4. The efficient stabilization of the cutter oscillation needed for the increase of the hole boring accuracy is obtained due to the time of adjustment $T = 0{,}8$ ms with the control action refining, which is 22 times faster (less) than in the system without damping the cutter form-building top oscillations and gives the possibility to take into account the main harmonic component of oscillations that causes the location and form error.
5. Technological capabilities of the developed equipment ensure control of cutter oscillations within the limits of the perturbation action from 0 to 35 μm, which is within the limits of allowances for the holes being bored on the transitions of the fine boring.
6. Based on the performed studies it was established that in the fine boring the location and form accuracy is most affected by the cutter top displacement under the action of the variable cutting forces, which cannot be compensated by the traditional methods. Use of the developed technological equipment permits: to increase 2.2 times on average the accuracy of the hole location in the selected range; to increase 1.59 times on average the accuracy of the hole form in its cross-section; when boring in the cutting modes at $V = 1{,}64$ m/s; $S = 0{,}05\text{-}0{,}2$ mm/rev; $t = 0{,}2$ mm, the 0,01 mm location error is ensured with the initial location error of 0,1 mm, and the cross-section form error ΔF no less than 0,008 mm.

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