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CALCULATION OF THE BORING BAR DESIGN FOR STATIC RIGIDITY AND STRENGTH WITH SIMULTANEOUS BORING OF A STEPPED HOLE WITH FURTHER OPTIMIZATION

Nurgul Karsakova[1], Karibek Sherov[2]*, Bakytzhan Donenbayev[1], Darmen Abulkhairov[2], Indira Sagynganova[3], Muratbek Usserbayev[2], Irina Teliman[1], Aibek Sherov[2], Gulim Tussupbekova[2]

[1] Karaganda Technical University named after A. Saginov, Ave. N. Nazarbayev 56, Karaganda, Kazakhstan
[2] Kazakh Agrotechnical University named after S. Seifullin, Victory Avenue 62, Astana, Kazakhstan
[3] Eurasian national university named after L.N.Gumilyov, Satpayev Str., 2, Astana, Kazakhstan
* shkt1965@mail.ru

A method for simultaneous processing of stepped holes in the bedding of a submersible pump and the boring bar design is proposed. The results of the study of existing methods for processing stepped holes and the design of boring tools are presented. It was revealed that the considered methods and designs of tools cannot be used for processing stepped holes in the submersible pump frame. The calculation of the developed design of the boring bar for static stiffness and strength, as well as the calculation of the stress-strain state (SSS) of the cutting plates by the finite element method using the ANSYS program, was carried out. The purpose of calculating the boring bar for static stiffness is a finite element study of the radial displacement of the boring bar cutter plates in the process of machining a stepped hole. As a result, the value of deformation in the axial and radial directions, which occur at the top of the cutting plate, is established. Also, the values of the cantilever overhang of the boring cutters are established, under which the conditions for the static rigidity of the boring bar are met. Taking into account the obtained results, the boring bar design was optimized.

Keywords: boring bar, hole boring, rigidity, strength, stepped hole, deformation

1 INTRODUCTION

There are problems associated with ensuring the required accuracy and quality of machining of critical surfaces during the manufacture of large parts of technological equipment. Such details include the frame of submersible pumps. The base of the SP8 submersible pump is its supporting part, on which the components and parts of the pump are mounted and to which especially high requirements are imposed in terms of its strength, rigidity and manufacturability [1],[2]. The bed in most cases is made of gray cast iron GC 15, GC18, GC21, GC32 [3],[4]. Fig. 1 shows a submersible pump frame made by casting.

1,2 - surfaces requiring high location accuracy

Fig. 1. The design of the submersible pump frame

"Maker LLP - KLMZ" and "QazKarbon LLP" factories are the main manufacturers of the submersible pump frame in Karaganda region. The technological process of machining the submersible pump frame is developed in different ways, depending on the level of the technological support of the particular machine-building enterprise. In the manufacture of the frame, special requirements are placed on ensuring the accuracy of the surface location 1 and 2 (see Fig. 1). It is difficult to ensure the accuracy of the surface location 1 and 2 under the conditions of the domestic machine-building industries (see Fig. 1). This may be due to the appearance of vibrations, the error in locating the part and fixing technological and tool equipment, wear of the cutting tool, control accuracy, etc. To develop a method for simultaneous processing of stepped holes and the design of a boring tool, the existing methods for processing the stepped holes and the boring tools design were investigated.

The work [5] presents the design of a special combined tool for processing deep base holes of rollers. The design of the tool allows the combination of two operations: fine boring and rolling. The paper defines the relationship between design and technological parameters, processes in the contact zone and quality indicators when processing with a combined tool. The main design parameters of the boring and rolling parts are selected.

In [6], new designs of two-stage progressive and two-stage spline broaches are proposed. The design of a two-stage progressive broach will reduce the pulling force and vibration, the specific pressure on the broach teeth, the depth of the defective layer, thereby improving the quality of processing cylindrical holes and tool life. The design of a two-stage splined broach with a straight-sided profile of single-cut splines with peripheral and side cuts can reduce the number of cutting teeth, broach length and tool material costs and increase economic efficiency.

In [7], a special design of a rotary friction tool with a self-rotating cup cutter for rotary friction boring of large diameter holes was developed. In order to ensure the quality and accuracy of processing, parametric optimization of the stressed components of a rotating friction tool was performed using virtual experiments in ANSYS WB. The calculation is made by the finite element method. The most widely used Johnson-Cook model was chosen as a criterion for the destruction of the finite element mesh elements.

The paper [8] presents the results of a study of the drilling process using a new cutting tool design - a sectional head with asymmetric carbide inserts of different widths. An engineering analysis of the proposed design was performed using APM WinMachine, which made it possible to design the tool with high quality and make functional decisions based on a comprehensive engineering analysis.

In [9], designs of broaches have been developed that will reduce the pulling forces and vibrations, as well as the specific pressure on the broach teeth. It is noted that the developed design of the tool helps to increase the durability of broaches, the quality of processing, saving tool material and economic efficiency.

In [10], a new design of a reaming multi-bladed broach drill for finishing holes is proposed. The combined drill-broaching tool is made of the high-speed steel with carbide inserts. The reaming multi-blade drill-broaching combines the properties of the reaming multi-blade drill (in cross section) and the properties of the broaching tool (in the longitudinal section).

The paper [11] presents the results of a study of the process of boring holes using a fixture with aerostatic supports. A feature of boring bars with aerostatic supports is that they are beams supported in two sections and loaded with a uniform load from their own weight. On both sides, the ends of the boring bars protrude from both sides, the system is statically indeterminate.

An experiment was carried out on three embedded devices with aerostatic supports. The relationship between the technological parameters of the boring bars and the accuracy of bored holes is determined.

The paper [12] presents the results of an experimental study of the method of rotational-friction boring of holes of the large diameters. The design of a special rotary tool for the implementation of the method of rotational-friction boring of the large diameters holes has been developed. Positive results were obtained and high results were achieved in the quality of the treated surface.

The performed studies of the existing methods of boring holes and the design of tools have shown that they cannot be used for processing stepped holes. A special design of the boring bar was developed [13],[14] for processing the stepped holes (see Fig. 1) of the “bed” part.

Fig. 2 shows a drawing of the process of boring stepped holes.

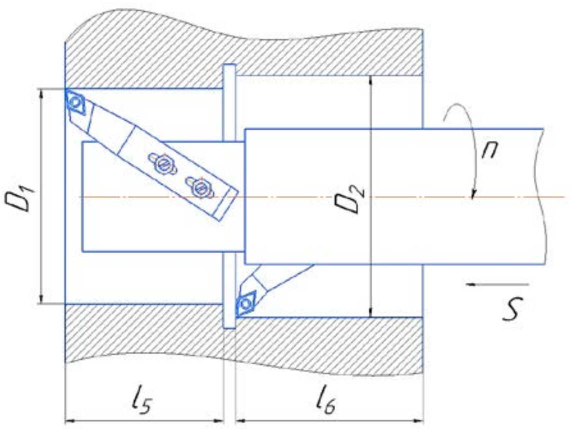


Fig. 2. drawing of the process of boring stepped holes

According to the working drawing of the frame, a stepped hole with dimensions of ø325 mm and ø295 mm is formed on surface 1. The use of the developed design of the boring bar for simultaneous boring of a stepped hole provides a reduction in the main and auxiliary time for processing, alignment and accuracy of the location of the machined surfaces, as well as an increase in productivity.

To optimize the parameters of a special boring bar, it is necessary to carry out calculations to determine the static and dynamic rigidity of the structure, the optimal dimensions of the overhang and the stress-strain state (SSS) of the cutting inserts. Distance from the body of the boring bar to the plate, i.e. the loose part of the cutter is called the overhang. The overhang determines the allowable boring depth and is the most important size of the boring tool. Excessive overhang causes excessive elastic deformation of the boring bar, introduces vibrations that degrade the surface quality, and can lead to premature wear of the insert. For most operations, it is necessary to select a boring bar with maximum static and dynamic rigidity. The static stiffness of the mandrel is its ability to withstand elastic deformations (squeezing) under the action of the cutting force. The dynamic stiffness of a mandrel is determined by its ability to dampen vibrations. In addition, the rigidity is affected by the material manufactured, shapes, dimensions and methods of fastening. Rigidity directly affects the quality index, the choice of cutting conditions and tool life.

The main disadvantage of boring is the cantilever mounting of the tool, which reduces the rigidity of the technological system. The main task is to study the radial displacement of the boring bar cutter plates in the process of machining a stepped hole and determine the size of the cutter overhang.

2 MATERIALS AND METHODS

2.1 Research method

The essence of the finite element method (FEM) lies in the fact that the area under consideration is divided into a large number of individual elements of a simple geometric shape, connected at the nodal points by superimposed bonds [15],[16]. Each element is assigned specific properties that are unchanged within each element. Necessary connections are imposed on the nodes that are common for the selected element and the rest of the body of the tool. Contact loads are applied to the elements of the working surfaces, after which the deformations and stresses in each element are determined.

Thanks to the development of computer technology, it has made it possible to use automatic finite element computer-aided design systems (CAD) [15],[17]. One of the most versatile software is ANSYS (a universal finite element analysis software system that has existed and developed over the past 30 years and is quite popular among specialists in the field of automated engineering calculations) [18]. In order to investigate the strength of tools, it is necessary to calculate the distribution of internal stresses of the tool cutting inserts. This problem is solved by the following steps using the ANSYS program: calculation of the components of cutting forces; creation of a three-dimensional model of the boring bar; The application of external contact loads on the front and rear surfaces of the cutting inserts; calculation of the SSS of cutting inserts by the finite element method using the ANSYS program.

2.2 Calculation of cutting force components

The cutting force R, it is customary to decompose into force components directed along the machine coordinate axes (tangential P_z, radial P_y and axial P_x) For external longitudinal and transverse turning, boring, cutting off, slotting and shaped turning, these components are calculated by the formula [19]:

$$P_{z,y,x} = 10C_p t^x s^y v^n K_n \qquad (1)$$

The cutting forces of the boring cutters of the boring bar will be calculated for two positions of the main angles in the plan φ^0: 1st position φ^0=60^0 for boring a hole with a diameter of 295mm; 2nd position φ^0=80^0 - for boring a hole with a diameter of 325mm. Grade of material of cutting inserts - VT8. The constant C_p and exponents x, y, n for specific processing conditions for each of the components of the cutting force are shown in Table 1 [19].

Table 1 - Cp constant and exponents x, y, n for boring

Processed material	Cutting Force Components	Coefficient and exponents in formulas for components			
		C_p	x	y	n
Gray cast iron, HB 190	tangential P_z	92	1	0.75	0
	radial P_y	54	0.9	0.75	0
	axial P_x	46	1	0.4	0

The correction factor K_p is the product of a series of coefficients ($Kp = K_{MP}K_{\varphi p}K_{\gamma p}K_{\lambda p}K_{rp}$), taking into account actual cutting conditions. The numerical values of these coefficients are given in Table 2 [19].

Table 2 - Correction factors that take into account the influence of the geometric parameters of the cutting part of the tool on the components of the cutting force when machining steel and cast iron

Parameters		Correction factors			
Name	Value	Desig-nation	The value of the coefficient for constituents		
			tangential P_z	radial P_y	axial P_x
Leading angle in the plan φ^0	60/80	$K_{\varphi p}$	0,94/0,89	0,77/0,5	1,11/1,17

Parameters		Correction factors			
Name	Value	Desig-nation	The value of the coefficient for constituents		
			tangential P_z	radial P_y	axial P_x
Front alloy angle γ^0	-10	$K_{\gamma p}$	1,25	2	2
Main Blade Angle λ^0	-5	$K_{\lambda p}$	1	0,75	0,66
Corner Radius r, мм	0,5	K_{rp}	0,87	0,66	1

$K_{MP} = \left(\frac{HB}{190}\right)^n = 1$ - correction factor for steel and cast iron, taking into account the influence of the quality of the processed material on the force dependencies, where n=0.4 is the exponent.

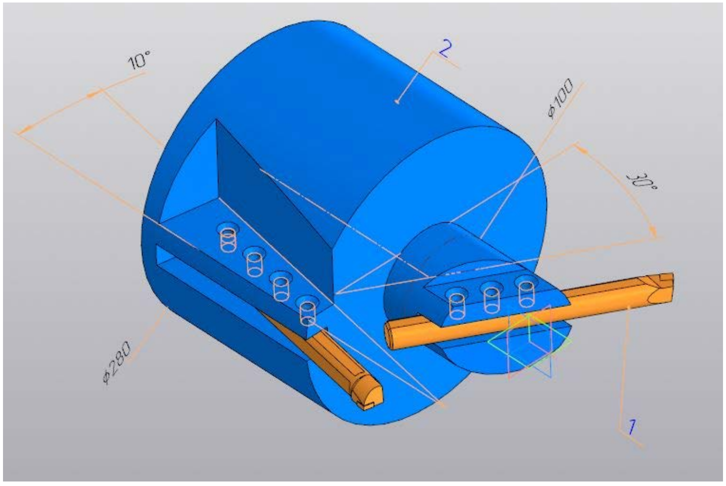
The calculated components of the cutting force, taking into account the correction factors according to the formula (1) in two positions of the boring cutter of the boring bar, are presented in Table 3.

Table 3 - Components of cutting force in two positions of the boring cutter of the boring bar

Processed material	Cutting Force Components, H	Positions of principal angles in the plan φ^0	
		60^0	80^0
Gray cast iron, HB 190	tangential P_z	532,6	562
	radial P_y	149,2	229,7
	axial P_x	1210	1147

2.3 Creating a 3D model of a boring bar

In order to investigate the SSS of the cutting inserts of a boring bar using the ANSYS program, it is first necessary to create a 3D model of the cutting inserts. A three-dimensional model of the boring bar was made in the Compass 3D software (Fig. 3).



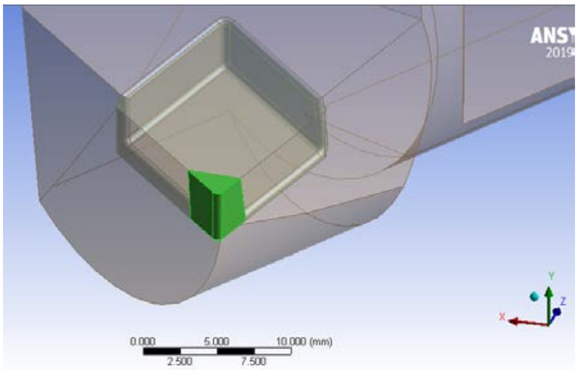
1 - boring cutter; 2 - body

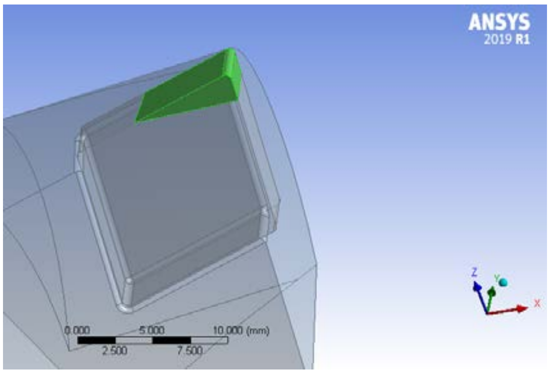
Fig. 3. Three-dimensional model of the boring bar

The angle of the first boring cutter in the plan is 60^0 for boring a hole with a diameter of 295mm, and the second one is 80^0 for boring a hole with a diameter of 325mm.

2.3.1 Application of cutting force components to the rake and flank surfaces of cutting inserts

In the Geometry section of the Ansys WB program, a part of the surface of the plates in contact with the workpiece during the boring process was selected for further application of cutting forces (Fig. 4).





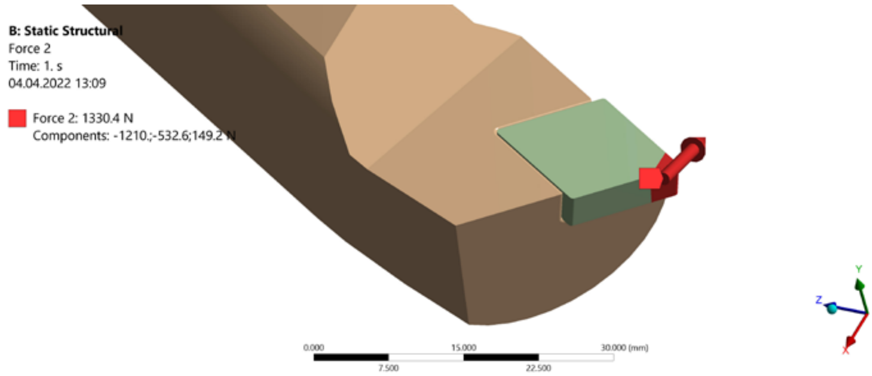
a) *b)*

a - 60^0 for boring a hole with a diameter of 295 mm; b - 80^0 for boring a hole with a diameter 325mm

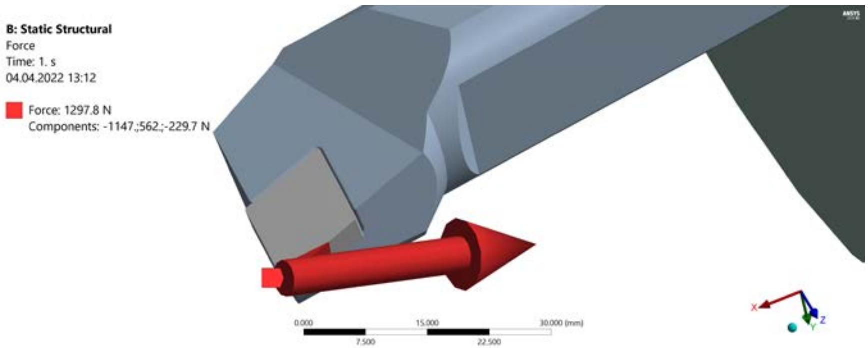
Fig. 4. Contact volumes

In the Static Structural item, the components of the cutting forces will be applied to the previously prepared surfaces according to the positions of the main angles in the plan φ^0 indicated above.

Fig. 5 The application of the cutting force components on the front and back surfaces of the cutting inserts.



a)



b)

a - 60^0 for boring a hole with a diameter of 295 mm; b - 80^0 for boring a hole with a diameter of 325mm

Fig. 5. The application of the components of cutting forces on the front and rear surfaces of the cutting inserts

2.4 Calculation of the stress-strain state (SSS) of cutting inserts by the finite element method using the ANSYS program

The finite element mesh of the boring rod is shown in Fig. 6.

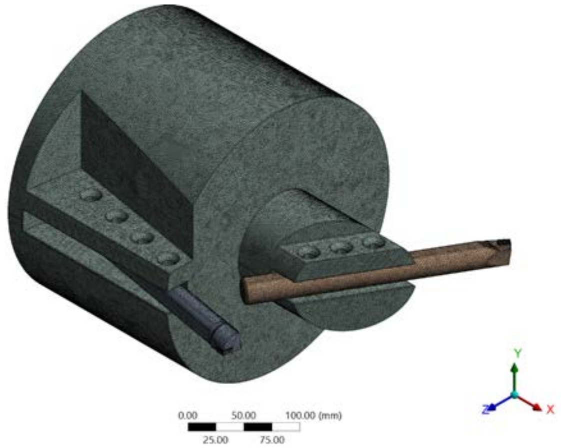
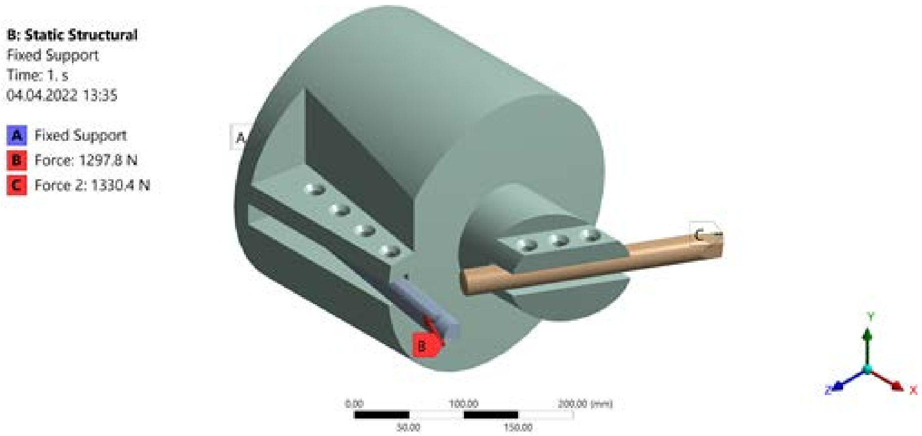


Fig. 6. Boring bar finite element mesh

Fig. 7 The boundary conditions for calculating the stiffness of the boring bar is showed.

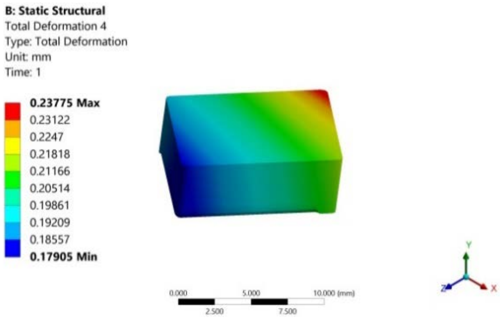


A - rigid sealing of the end of the body of the boring bar; B - cutting force components when boring a hole with a diameter of 325 mm; C - components of the cutting force when boring a hole with a diameter of 295mm.

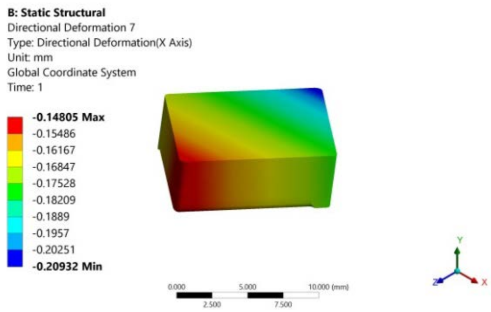
Fig. 7. Boundary conditions for calculating the rigidity of the boring bar

The results of the calculation of the stress-strain state of the boring bar are below.

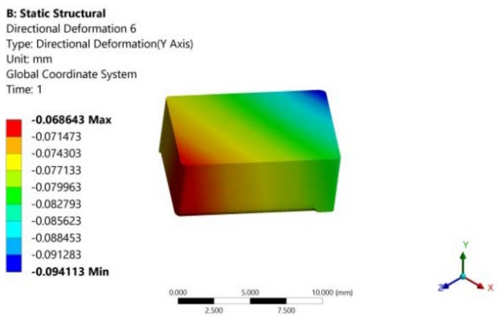
Fig. 8 The deformation of the cutting insert when boring a hole with a diameter of 295mm is showed.



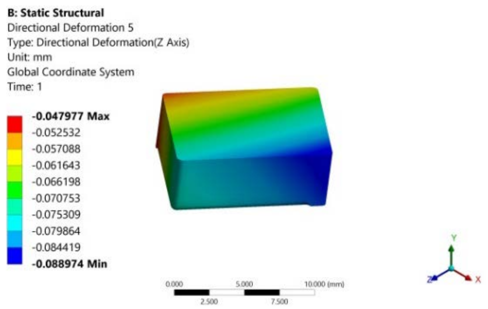
a)



b)



c)

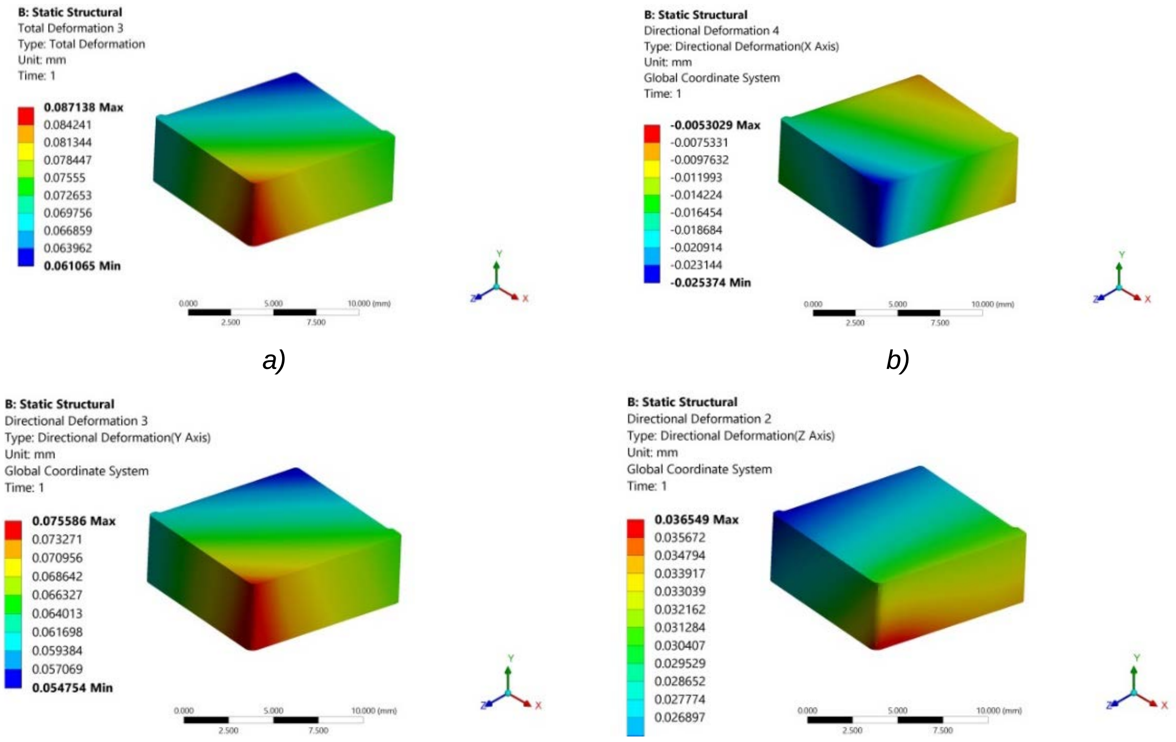


d)

a - resulting deformation; b - X - in the axial direction; c - Y - in the circumferential direction; g - Z - in the axial direction

Fig. 8. Deformations of the cutting insert when boring a hole with a diameter of 295mm

Fig. 9 The deformation of the cutting insert in axial coordinates when boring a hole with a diameter of 325mm is showed

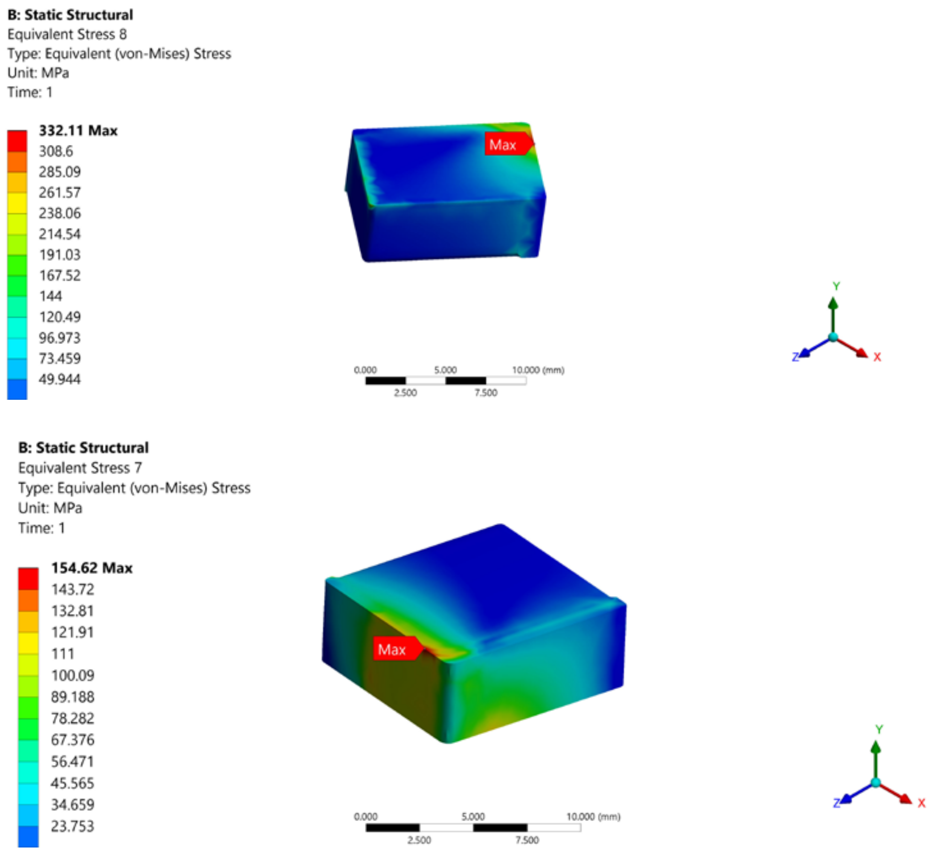


a) b) c) d)

a - resulting deformation; b - X - in the axial direction; c - Y - in the circumferential direction; g - Z - in the axial direction

Fig. 9. Deformations of the cutting insert when boring a hole with a diameter of 325mm

Fig. 10 The equivalent stresses according to Mises for cutting inserts with the hole diameters 295mm and 325mm are showed



a) b)

a - 60^0 for boring a hole with a diameter of 295 mm; b - 80^0 for boring a hole with a diameter 325mm

Fig. 10. Equivalent stresses according to Mises

2.5 Optimization of tool design

The purpose of optimizing the tool design is to reduce the overall dimensions while observing the condition of boring bar design rigidity. Optimization of tool design was carried out based on methods given in the works [7], [20], [21].

As optimization criterion the radial displacement (along Z-axis) of the feed cutter blade tip was selected, directly influencing the machining quality, including it is the furthest from the mounting surface. For this purpose, the two parameters holder diameter (D), fixture thickness of the first cutter (t1) are chosen and the parametrical model of boring bar is constructed (fig. 11). Minimum values of parameter of boring bar body: D=50 mm, t_1=10 mm (fig. 12, a); maximum - D=150 mm, t_1=15 mm.

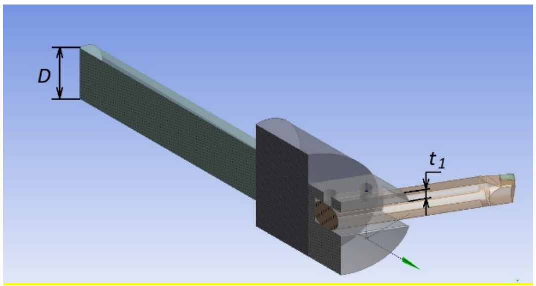
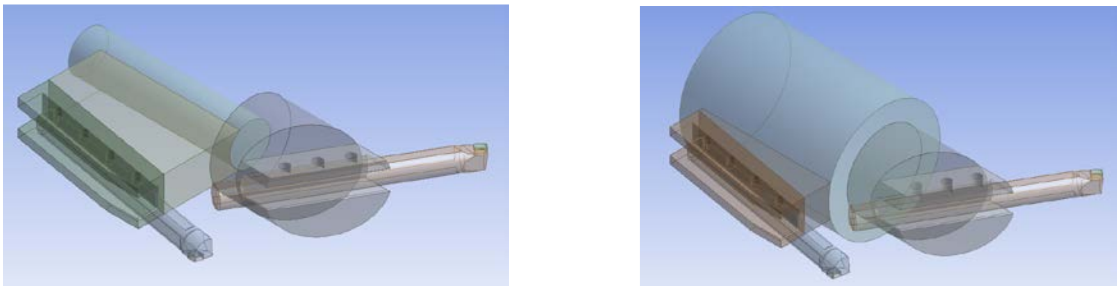


Fig. 11. Parametric model of the boring bar



a) b)

a) minimum parameters; b) maximum parameters

Fig. 12. Boring bar design:

The central composite and depending on the input parameters (columns B and C) in the program Ansys WB generated output parameters (column D) - the radial displacement (along the axis Z) of the cutter blade tip (table 4).

Table 4 - Central Composition Plan

	A	B	C	D
1	Name	P1 - t1 (mm)	P4 - D (mm)	P8 - Directional Deformation 9 Average (mm)
2	1	12,5	100	-0,063405
3	2	10	100	-0,063762
4	3	15	100	-0,063119
5	4	12,5	50	-0,070393
6	5	12,5	150	-0,062481
7	6	10	50	-0,070764
8	7	15	50	-0,070243
9	8	10	150	-0,062708
10	9 DP 0	15	150	-0,062088

As a result, the response surface of the radial displacement from two parameters (D and t_1) was obtained (Fig. 13).

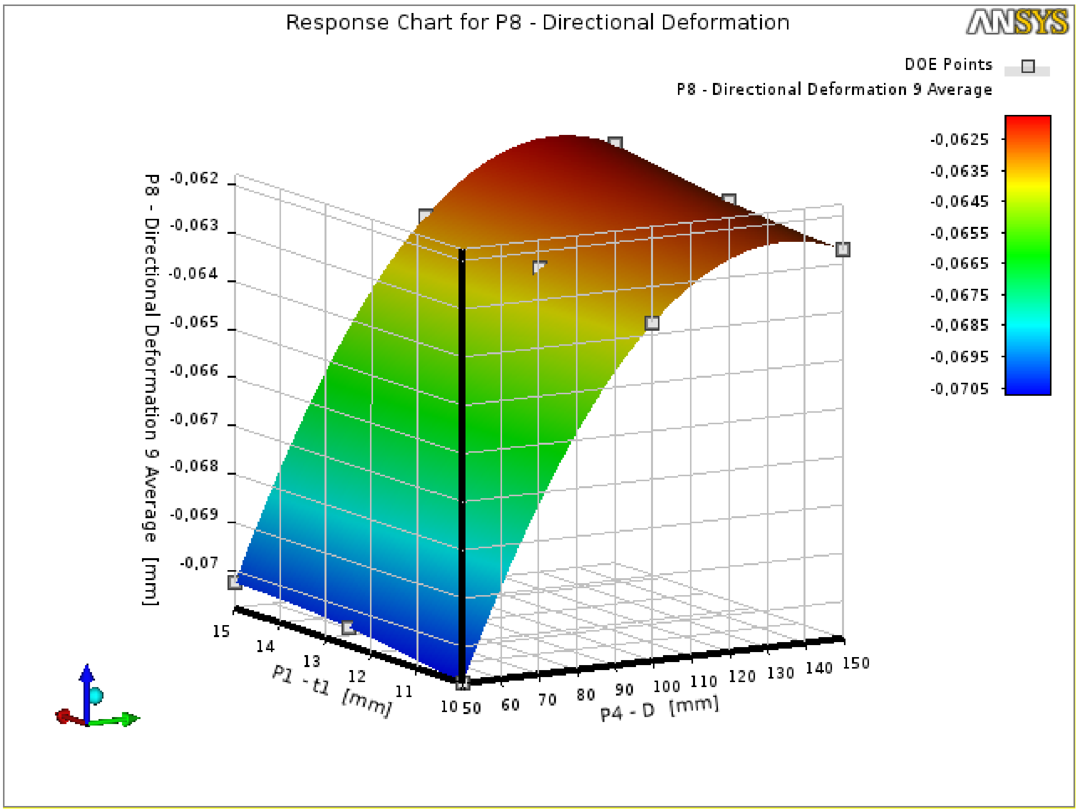


Fig. 13. Response surface of radial displacement from two parameters

Next, to determine the highest point on the response surface, optimization by Screening method is carried out, as a result of which candidate points will be given out. To narrow the area of search for optimal parameters the range of optimization criterion is given (Table 5).

Table 5 - Constraint condition of the optimization criterion

	A	B	C	D	E	F	G
1	Name	Parameter	Objective		Constraint		
2			Type	Target	Type	Lower Bound	Upper Bound
3	-0,062 mm <= P8 <= -0,06 mm	P8 - Directional Deformation 9 Average	No Objective		Lower Bound <= Values <= Upper Bound	-0,062	-0,06
*		Select a Pa...					

As a result, three possible optimal boring bar parameters were obtained (Table 6).

Table 6 - Possible optimal parameters of the boring bar

	A	B	C	D	E	F
1	Reference	Name	P1 - t1 (mm)	P4 - D (mm)	P8 - Directional Deformation 9 Average (mm)	
2					Parameter Value	Variation from Reference
3	○	Candidate Point 1	13,698	127,88	★★★ -0,061984	-0,13 %
4	◉	Candidate Point 2	14,138	136,28	★★★ -0,061904	0,00 %
5	○	Candidate Point 3	14,718	146,05	★★★ -0,061998	-0,15 %

On "column E" parameters of a boring bar corresponding to the lowest value of radial movement (the highest point on the surface of the response), that is D=136 mm, t_1=14 mm were chosen (fig. 14).

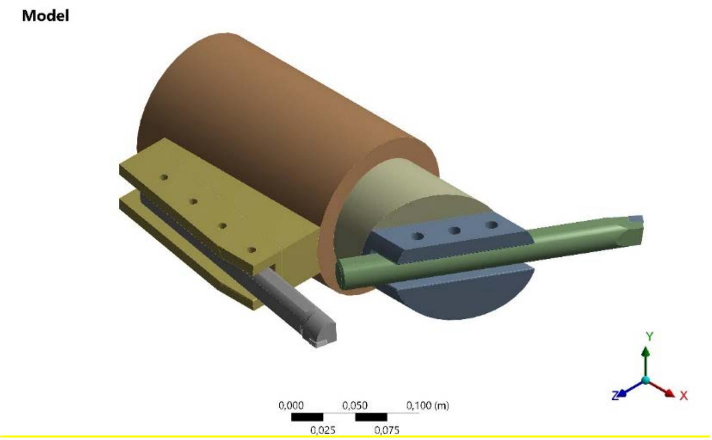


Fig. 14. Three-dimensional model of a boring bar with optimal parameters

A verification calculation for the stiffness of the boring bar structure with optimal parameters was performed. For more rational partitioning into finite elements, the complex configuration of the boring bar body was initially broken down into separate arrays and then glued together (Fig. 15).

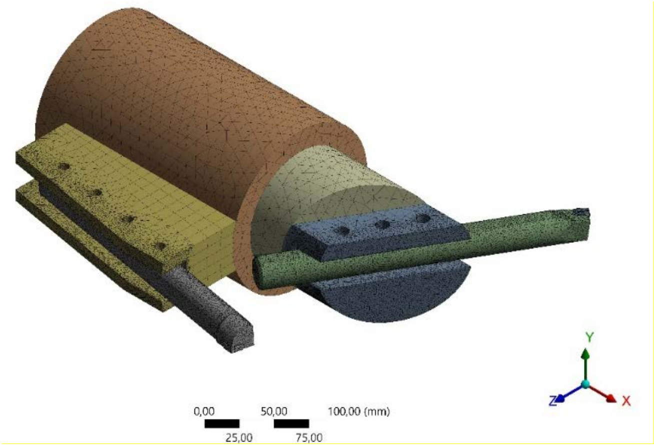


Fig. 15. Rational finite element grid of the boring bar

The deformation of the boring bar body is shown below (Fig. 16).

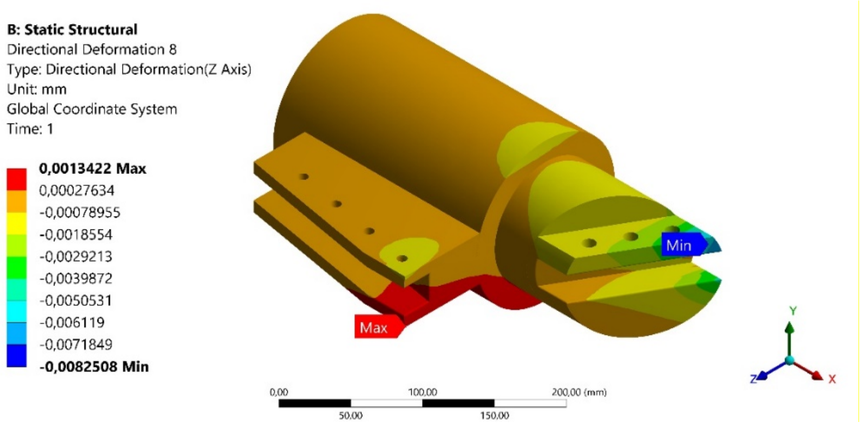


Fig. 16. Deformation of the boring bar body

Note that the maximum values of deformation by module arise as above said in places farthest from the surface of the boring bar fastening.

Also radial deformations on the cutting cutter blade tips were determined (fig. 17).

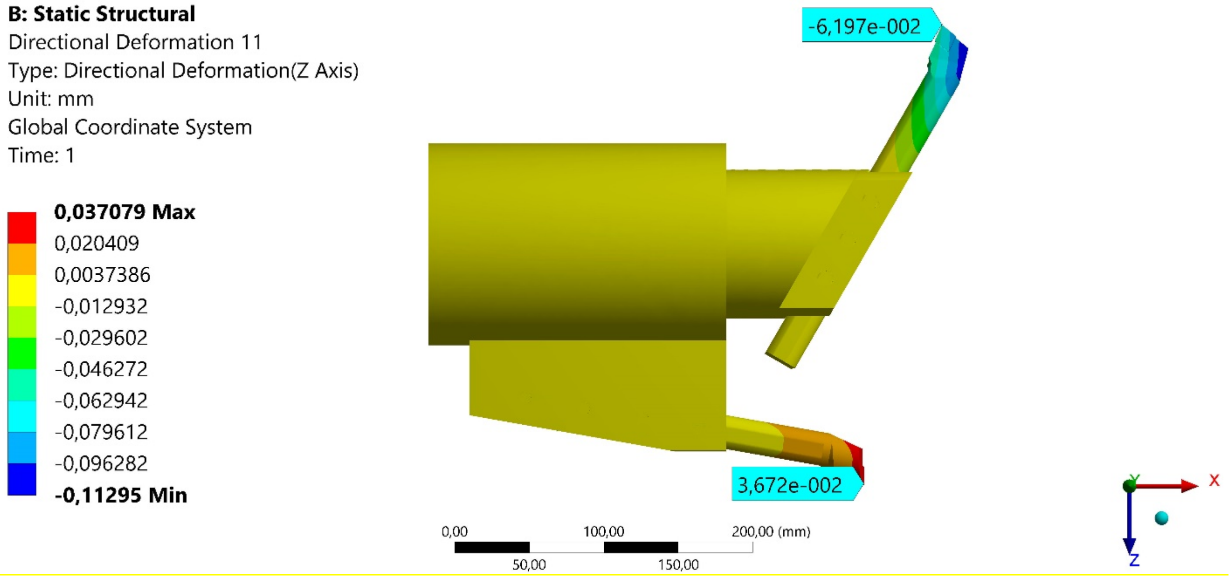


Fig. 17. Radial deformations at the tips of cutter blades

The radial displacement practically corresponds to this obtained from Table 6.

3 RESULTS AND DISCUSSION

The key deformation that directly affects the accuracy of processing the inner wall of a hole with a diameter 295 mm is the deformation along the Z axis at the top of the plate along the contact, that is, coinciding with the radial direction of the hole. Note that the radial (along the Z axis) strain value corresponds to 62 µm (see Fig. 8).

Boring a hole with a diameter 325 mm differs from boring a hole with a diameter 295 mm in that the inner and end surfaces are machined simultaneously (see Fig. 9). And accordingly, it is necessary to pay attention to the deformations at the top of the plate in two directions: radial and axial. The face machining is affected by the deformation along the X-axis (axial direction) and it is 23.8 µm. And the radial strain value at the tip of the cutting insert is 36.2 µm (see Fig. 9).

At first glance, it seems that the equivalent stresses of the cutting inserts when boring a hole with a diameter 325 mm will be greater than when boring a hole with a diameter 295 mm, but according to Figure 10a, b it is obvious that the stress when boring a hole with a diameter 325 mm is 154.62 MPa, and when boring holes with a diameter 295 mm is 332.11 MPa.

I would like to note that in this calculation, the connection points of the boring bar are idealized and considered without gaps. In reality, the accuracy and processing errors are made up of the tolerances of the connected elements. A series of calculations of the boring bar was carried out with a change in the overhang of the boring cutter until the condition of the static rigidity of the boring bar as a whole was met, and the optimal cantilever overhang was chosen, it is 95 mm and 108 mm.

The radial movement of the cutting insert when boring a hole with a diameter 295 mm affects the accuracy and corresponds to the deformation along the global Z axis, and amounted to 0.062 mm or 62 µm. When boring a hole with a diameter 325 mm, attention should be paid to deformations at the top of the plate in two directions: radial and axial, which are 0.0362 mm or 36.2 microns and 0.0238 mm or 23.8 microns. The equivalent stresses of cutting inserts when boring a hole with a diameter 325mm will be greater than when boring a hole with a diameter 295mm.

Optimal parameters of the boring bar body were selected to ensure the accuracy of machining.

The maximum deformation occurs in places farthest from the boring bar mounting surface.

For more rational partitioning into finite elements the complex configuration should be divided into separate arrays.

4 CONCLUSIONS

As a result of the study of the technology for manufacturing the part of the frame of the NP8 submersible pump in the conditions of the factories of "Maker" LLP and "QazKarbon" LLP, it was found that it is difficult to ensure the accuracy of the location of functionally interconnected surfaces of the stepped holes. To solve this problem, a method for simultaneous boring of stepped holes and the design of a special boring bar are proposed.

Calculation of the boring bar for static rigidity was carried out by means of a finite element study of the radial displacement of the plates of the cutter of the boring bar directly in the process of processing a stepped hole. As a result, the following are established:

- deformation at the top of the cutting insert appears in the radial and axial directions. The strain value in the axial direction is 23.8 µm and in the radial direction 36.2 µm;

- the values of the cantilever overhang of the boring cutters are set to 95 mm and 108 mm, under which the conditions for the static rigidity of the boring bar are met;
- it was found that the equivalent stresses of the cutting inserts when boring a hole with a diameter of 325 mm are greater than when boring a hole with a diameter of 295 mm.

The tool design was optimized and the optimal parameters of the boring bar body were selected to ensure the accuracy of processing.

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