

# Influence of the Rigid Connection Between Discs in the Tetrahedral Prisms on Equivalent Stresses When Cutting Work Faces

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**Abstract.** This paper presents the results of modeling of the stressed state of structural elements of the paired fastening points of the two disc tools to the tetrahedral prisms of the working bodies of the roadheaders of selective action when cutting work faces of heterogeneous structure. The advantages of cooperative mode rotation to separate two disc tools on each of the tetrahedral prisms placed between the axial cutting crowns.

## Introduction

Currently, Gorbachev KuzSTU, the Department of Mining Machinery of the Institute of Mining, together with Yurga Institute of Technology, TPU Affiliate, the Department of Mining Equipment, are engaged in researches with the purpose of developing and improving designs of mounting points to hold cutting tools intended for cutting heads in tunneling machinery. These studies are implemented in phases and permits modeling of the stress-strain state of mating elements in points of mounting disk cutters, which are different in designs, supported by brackets and polygonal prisms located on cutting heads of selective roadheaders and geokhods while mining non-uniform in structure working faces [1–15].

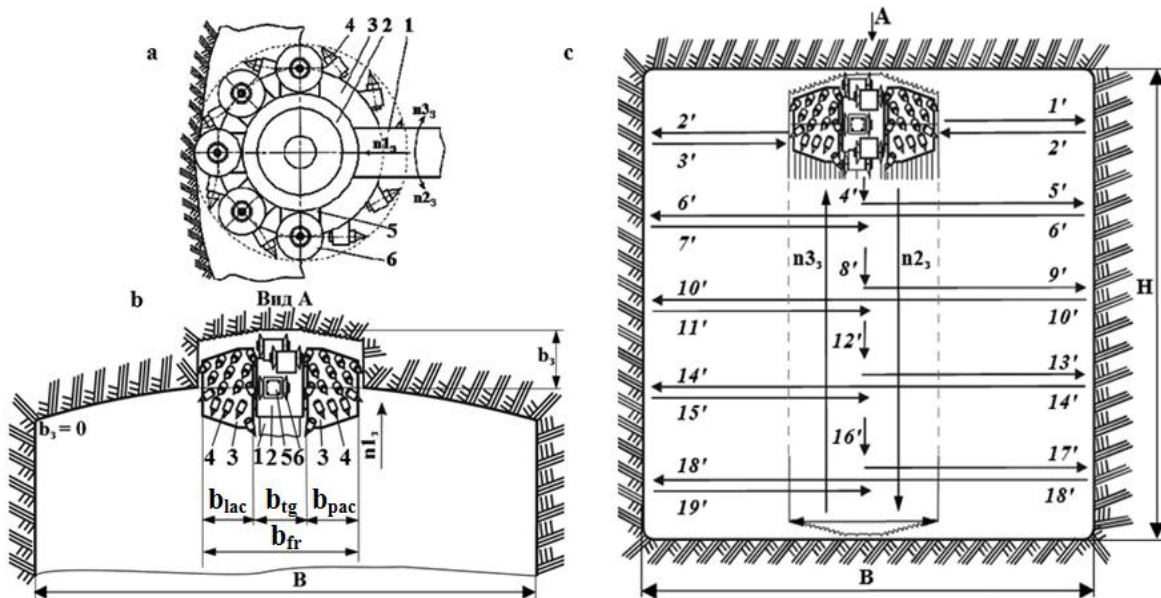
## 2. The device and principle of operation of the working body of the roadheader of selective action with built-in disk tool

The main disadvantage of a number of selective roadheaders with transverse cutter heads is that the performance of the cutting process is low due to the presence of non-crushed rock masses in space between cutting drums, and this requires additional reciprocating rotary movements of the boom in the horizontal plane. To enhance the efficiency of cutting processes performed by a selective roadheader, having cutting heads with cross-axial cutting drums that are separated from each other by a gearbox casing, the technical solution is suggested (Russian patent 136086) that disk cutters mounted in tetrahedral prisms are positioned in the inter-drum space (Figure 1) [4, 5].

The cutter head of a selective roadheader (Figure 1, a, b) comprises a boom 1, a casing of a transfer gear box 2 with two axial cutting drums 3 having bits 4. Tetrahedral prisms 5 with two disc cutters 6 are attached to the cylindrical surface of the gearbox casing 2. By means of six hydraulic cylinders, the



cutter boom 1 can move in three directions relative to the stationary roadheader body. Two hydraulic cylinders provide the telescopic axial action in direction  $n1_3$ , two hydraulic cylinders are used for raising and lowering the boom 1 in the vertical direction along the arrows  $n2_3$  and  $n3_3$ , and two hydraulic cylinders ensure the swinging motion of the boom in the horizontal direction to walls of excavation.



**Figure 1.** A cutter head with point bits and disk tools: a – a space to place disk cutters; b – the sump in the centre of a working; c – the sequential tunneling cutting process

The inner space of the tetrahedral prism 5 with mounting points to hold the disk tool 6 is closed by a sealing four-sided cover. In this case, the diameter of circle (Figure 1, a) circumscribed about outer edges of the disk tools 6 in a plane perpendicular to the axis of rotation of the cutting drum 3 is not greater than the diameter of circle circumscribed about maximum radius of the outer bits 4 on large basements of the axial cutting drums 3.

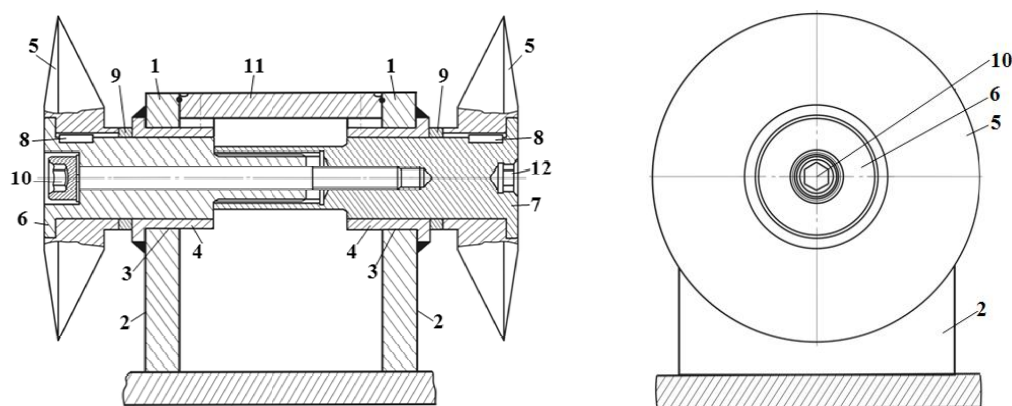
Cutting heads of a selective roadheader perform cyclical excavation of a rectangular section with a height  $H$  and a width  $B$  (Figure 1, b, c). Before starting the excavating operations, the cycle begins with a cut in the central part of a working. When the first cut is made using two axial cutting drums to a desired amount of cut in the direction of the longitudinal axis of development, or the width of web  $b_3$  (Figure 1, b), reciprocating cyclic movements of the boom in the vertical plane from the roof to the ground  $n2_3$  and back,  $n3_3$ , is combined with a gradual telescoping  $n1_3$  to the specified widths of web  $b_3$ . This process is enabled by simultaneous operation of the hydraulic cylinders to raise the boom, the hydraulic cylinders to extend the boom and a continuous rotation of two axial cutting drums. The sump making is carried out over the width of cut front  $b_{fr}$ , including the width of cut made by the left  $b_{lac}$  and right  $b_{pac}$  axial cutting drums, as well as the width  $b_{tg}$  of the transfer gearbox casing in the form of a cylinder sector with a coverage angle of  $\varphi \leq \pi/2$ , to the surface of which the tetrahedral prisms with two disk tools are attached according to a certain arrangement scheme, operating as a pivoting blade installation.

After the sump formed, it is possible to use a trajectory of the boom with the axial cutting drums following along the directions of motion  $1'-19'$  (Figure 1, c). The processes of crushing are dominated in the direction of motion  $1'-11''$ , and in the direction of motion  $1'-3'$ ,  $17'-19'$  there are the processes of crushing, cutting of ragged cuts and asperity on the roof and ground surfaces. After the final cleaning – up the ground from cut masses across the width  $B$  of a working, the boom-type roadheader

advances towards the face, and using the hydraulic cylinders for telescoping, the boom retracts by an amount of  $b_3$  and the next cut cycle of excavation commences.

The results of research are presented in the works referenced in [4, 5] on modeling the stress state of mating elements in mount points to hold two disk cutters in tetrahedral prisms in decoupled modes of rotation when forming a sump in centre of the working face.

To study the state of stress in the mounting points used for holding the disk tool in the tetrahedral prisms during the operating mode of simultaneous rotation, with a selective roadheader forming a sump in the center of the working, the inventive technical solution (Russian patent 146845) has been proposed that includes a tetrahedral prism with twinned disk tools (Figure 2) [5]. Implementing this technical solution allows the simultaneous rotation of two disk cutters held in each tetrahedral prism, with resulting in reducing their jamming and wearing -out during the sump process made by the cutting head of a boom-like roadheader in rock mass.



**Figure 2.** Rigid connection of two disc cutters in a tetrahedral prism

The tetrahedral prism 1 (Figure 2) consists of two working faces 2 having trough cylindrical holes 3 and two side faces. A tubular member 4 is placed inside each cylindrical hole 3. In addition, twin disc cutters 5 are in the form of a single detachable functional modular unit that is able to rotate freely and simultaneously relative to the fixed tubular members 4. The single detachable functional modular unit comprises two axes 6 and 7 with thrust collars, rigidly attached to each other, one axle includes a spline drive and the other contains a spline bush. The axles 6 and 7 have places to provide keyed connection of the disk cutters 5 using the fixing key 8. Distant side washers 9 are placed between the side surfaces of either of two disk cutters 5 and the side surface of the thrust collars of either of two tubular members 4. The axle 6 has a stepped through hole, inside of which a distance screw 10 is located for fixing the detachable functional modular unit. A tetrahedral cap 11 is used to protect the interior space of the tetrahedral prism 1. On the free end of the axle 7 there is a hexagon opening 12 for a wrench used for assembling and dismantling operations.

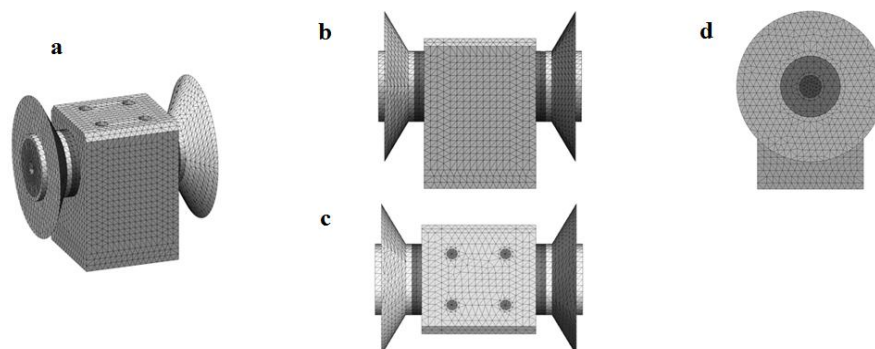
### 3. Modeling of the stress state of structural elements of the attachment disk tool for joint rotation mode

Making finite element models (Figure 3) and calculating stress forces  $P_z$ ,  $P_y$ ,  $P_x$  (Table 1) for the twinned disk tool with mounting points on the tetrahedral prisms are performed using the procedures set out in the research works relating to cutting heads having reversible radial drums and tools with one disc cutter, supported in brackets and triangular prisms, as well as axial drums and tools with two separate disc cutters supported in tetrahedral prisms [1–5].

For calculating parameters of stress state, the following characteristics of mined working faces were taken as initial conditions: coal ( $\sigma_{\text{compr}} = 12.4; 13.5; 14.8$  MPa) and rock ( $\sigma_{\text{compr}} = 51; 60.6; 78.9$  MPa). To simulate the stress-strain state of the mating elements in the mounting points, four possible designs

of a disk cutter with a diameter  $D = 0.16$  m (three biconical designs having taper angles:  $\varphi = \varphi_1 + \varphi_2 = 25^\circ + 5^\circ = 30^\circ$ ;  $20^\circ + 10^\circ = 30^\circ$ ;  $15^\circ + 15^\circ = 30^\circ$  and one conical  $\varphi = 0^\circ + 30^\circ$ ).

The SolidWorks Simulation package, with considering general problems of solving linear systems using the finite element method (FEM), was used for modeling the stress-strain state of the mating elements in the points of mounting the twinned disk tools to the tetrahedral prisms located on the transfer gearbox casing in the space between the drums of the cutter heads used in selective roadheaders. In discretizing geometric models, the grid with parabolic finite elements (FE) in the form of tetrahedrons was used. The parabolic FE provide a better description of geometry of the model by the grid and increased accuracy of calculations by means of more nodes if compared with linear finite elements. The size of the finite elements was selected so as a further increase in the grid density had no significant effect on the results of calculations. The grid settings: FE size - 10 mm; tolerance - 0.5 mm; automatic grid density was not used. For the calculation, the algorithm FFEPlus was used, as it is more efficient for solving large-scale problems. To describe the interaction of parts in assembly the following contact conditions were used: for rigid connections of elements of the case - the type of contact conditions "related" and for detachable connections - contact condition "no penetration".

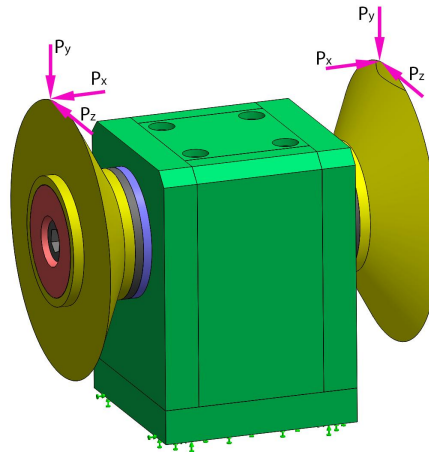


**Figure 3.** The finite element model of the tetrahedral prism with the twinned disk tools: a - in perspective; b, c, d - three main projections

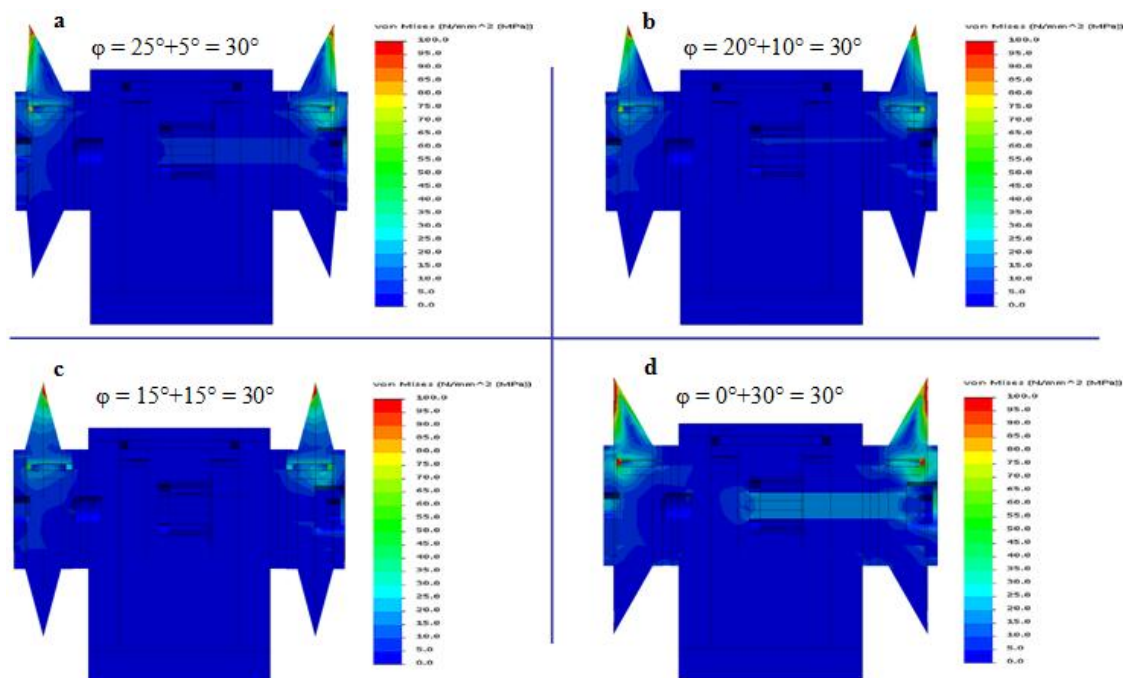
Table 1. Calculated loads when cutting a work face using the twinned disk tool

	Description of a work face in $\sigma_{\text{compr}}$ , MPa					
Force, kN	Coal			Rock		
	12.4	13.5	14.8	51	60.6	78.9
	When $h = 0.04\text{ m}$			When $h = 0.006\text{ m}$		
	Biconical disc tool: $\varphi = \varphi_1 + \varphi_2 = 25^\circ + 5^\circ = 30^\circ$					
P <sub>z</sub>	4.946	5.255	5.812	3.548	4.216	5.489
P <sub>y</sub>	11.11	11.737	13.054	11.009	13.082	17.033
P <sub>x</sub>	0.323	0.314	0.318	4.337	5.154	6.71
	Biconical disc tool: $\varphi = \varphi_1 + \varphi_2 = 20^\circ + 10^\circ = 30^\circ$					
P <sub>z</sub>	5.003	5.286	5.879	3.589	4.26	5.553
P <sub>y</sub>	11.239	11.873	13.205	11.137	13.23	17.23
P <sub>x</sub>	0.327	0.317	0.322	4.388	5.21	6.788
	Biconical disc tool: $\varphi = \varphi_1 + \varphi_2 = 15^\circ + 15^\circ = 30^\circ$					
P <sub>z</sub>	5.101	5.389	5.994	3.659	4.348	5.662
P <sub>y</sub>	11.458	12.105	13.463	11.354	13.492	17.566
P <sub>x</sub>	0.333	0.324	0.328	4.473	5.315	6.921
	Conical disc tool: $\varphi = \varphi_1 + \varphi_2 = 0^\circ + 30^\circ$					
P <sub>z</sub>	4.927	5.205	5.79	3.535	4.2	5.469
P <sub>y</sub>	11.068	11.692	13.004	10.968	13.032	16.968
P <sub>x</sub>	1.739	1.837	2.043	4.321	5.134	6.685

The cutting force  $P_z$ , the sump force  $P_y$  and side force  $P_x$  on the twinned disk cutters (Figure 4) were determined, taking into account the constructive and performance parameters, and characteristics of the worked face  $\sigma_{\text{compr}}$ . The calculated forces  $P_z$ ,  $P_y$ ,  $P_x$  (Table 1) were applied to the finite element model of disk cutters mounted in the tetrahedral prism with the purpose of obtaining the stress state pictures (Figure 5-8) relating to biconical and conical disk tools, with considering the tensile strength under uniaxial compression of rock mass  $\sigma_{\text{compr}}$  ranging 12.4 to 78.9 MPa. The following steels were used for making mating elements: 35HGSA, St 45, St 65G, St.15.

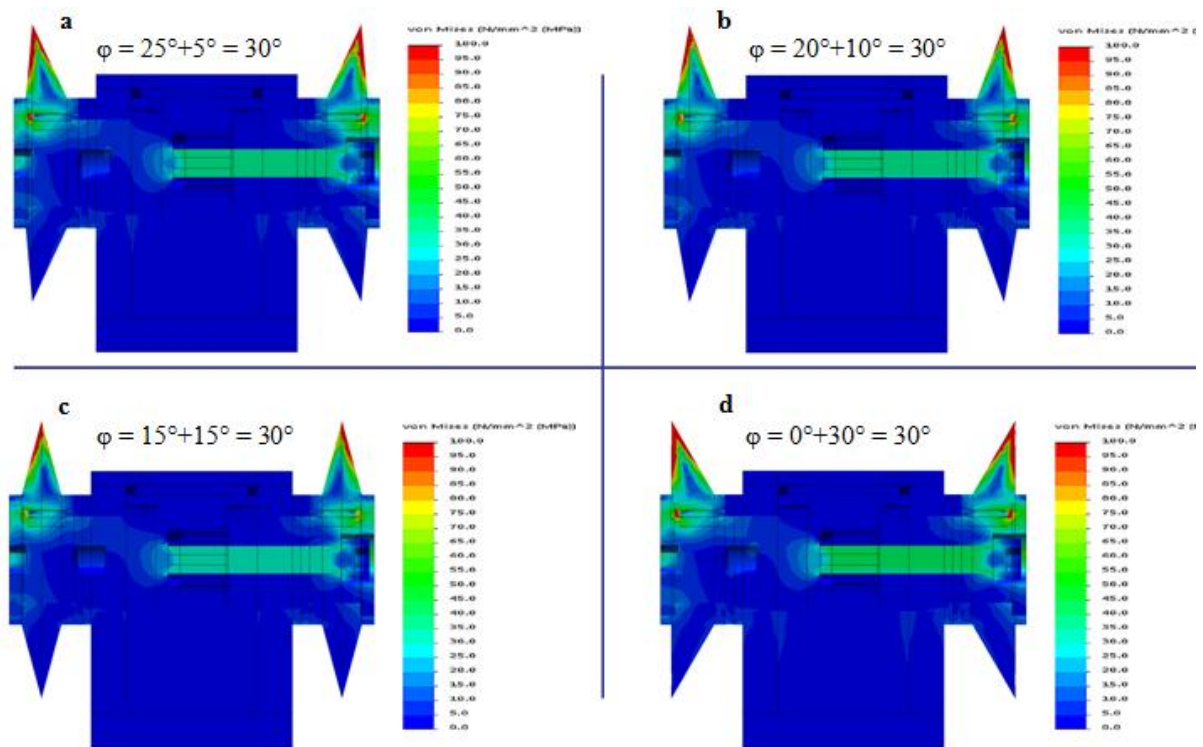


**Figure 4.** Diagram of applying forces to discs and mounting points of the tetrahedral prism

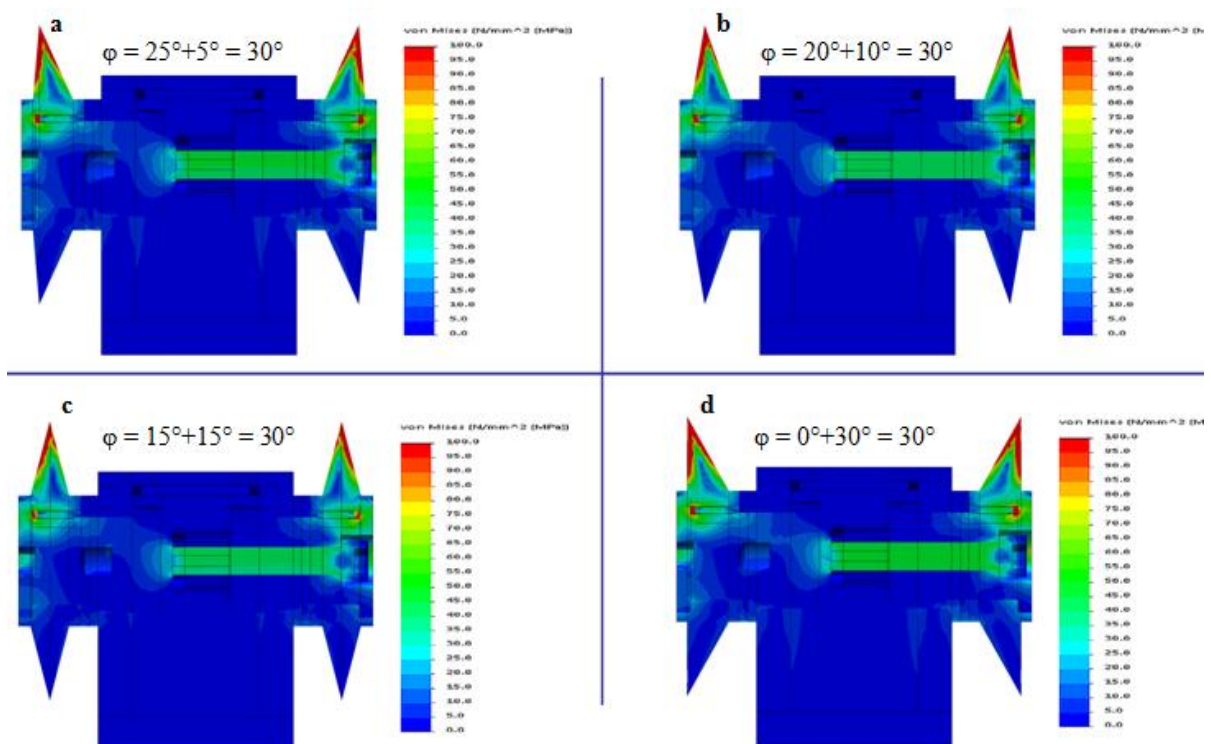


**Figure 5.** The distribution of equivalent stresses according to von Mises criterion in the mounting points of the twinned disk tools when cutting a coal face  $\sigma_{\text{compr}} = 12.4$  MPa

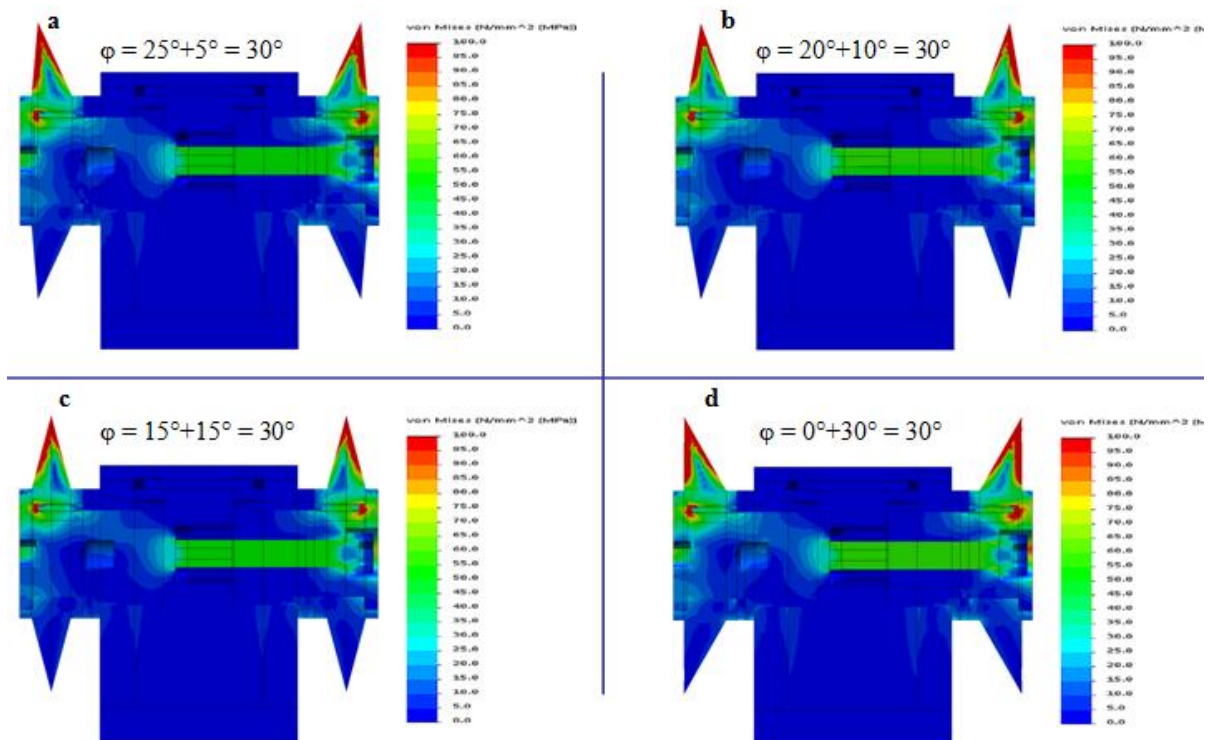




**Figure 6.** The distribution of equivalent stresses according to von Mises criterion in the mounting points of the twinned disk tools when cutting rock mass  $\sigma_{\text{compr}} = 51 \text{ MPa}$

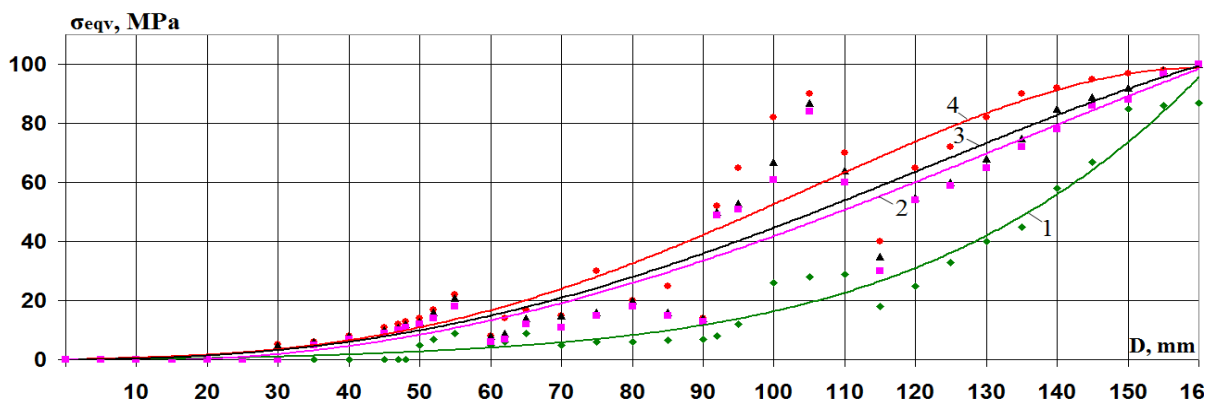


**Figure 7.** The distribution of equivalent stresses according to von Mises criterion in the mounting points of the twinned disk tools when cutting rock mass  $\sigma_{\text{compr}} = 60.6 \text{ MPa}$

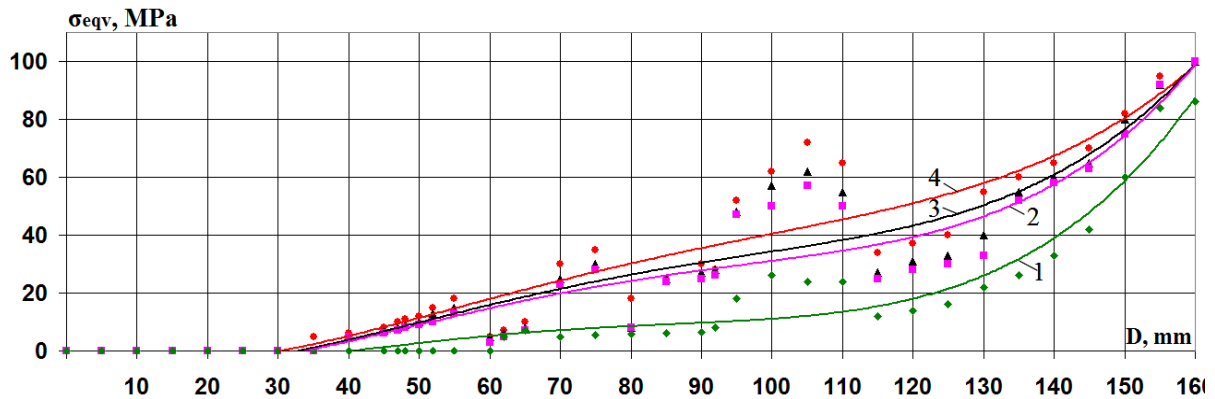


**Figure 8.** The distribution of equivalent stresses according to von Mises criterion in the mounting points of the twinned disk tools when cutting rock mass  $\sigma_{\text{compr}} = 78.9$  MPa

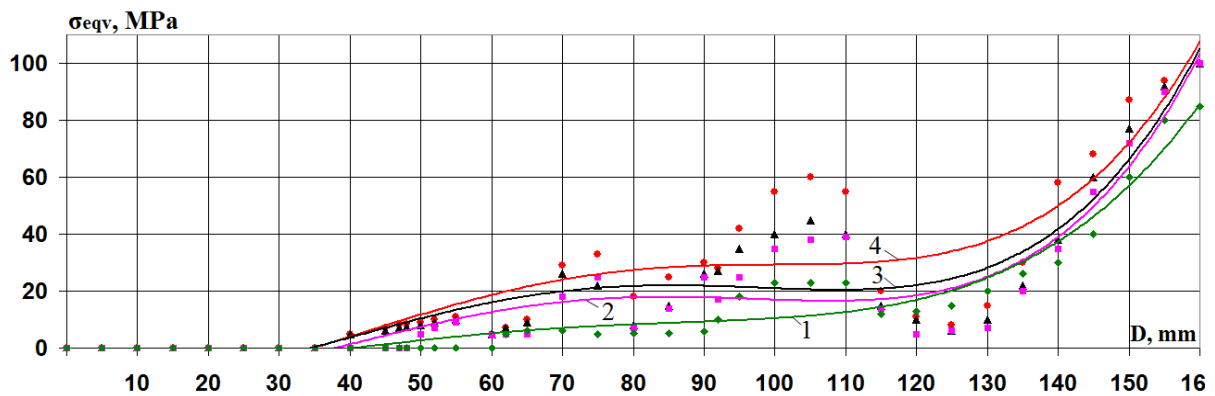
Figures 9-12 show the dependencies of equivalent stresses according to von Mises criterion  $\sigma_{\text{eqv}}$  on the diameter  $D$  of the disk tool in the plane of section over the V-flange edge on the part of the fixing screw for the simultaneous rotation mode of disks when cutting: a coal face (1 –  $\sigma_{\text{compr}} = 12.4$  MPa), rock mass (2 –  $\sigma_{\text{compr}} = 51$  MPa; 3 –  $\sigma_{\text{compr}} = 60.6$  MPa; 4 –  $\sigma_{\text{compr}} = 78.9$  MPa).



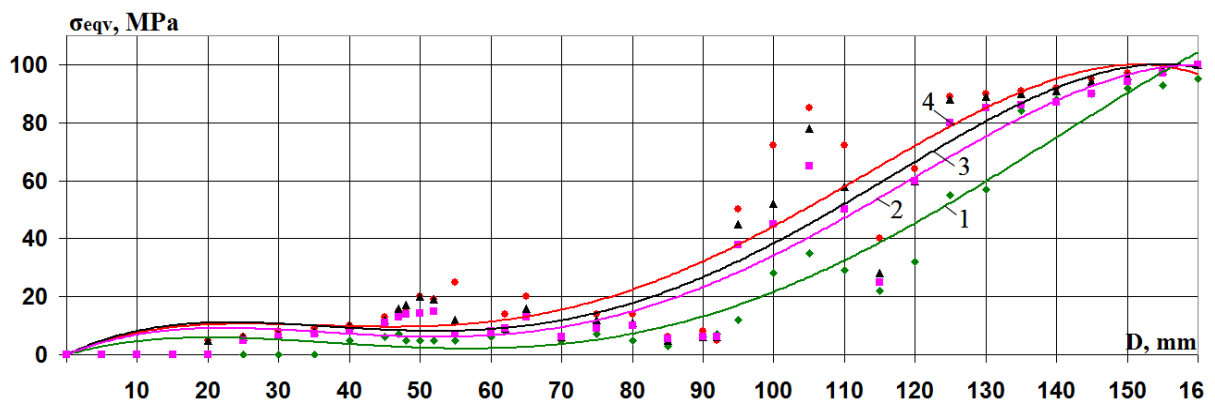
**Figure 9.** Dependencies of the equivalent stresses  $\sigma_{\text{eqv}}$  on the diameter  $D$  of the biconical disk tool with the taper angle  $\varphi = 25^\circ + 5^\circ = 30^\circ$



**Figure 10.** Dependencies of the equivalent stresses  $\sigma_{eqv}$  on the diameter  $D$  of the biconical disk tool with the taper angle  $\varphi = 20^\circ + 10^\circ = 30^\circ$



**Figure 11.** Dependencies of the equivalent stresses  $\sigma_{eqv}$  on the diameter  $D$  of the biconical disk tool with the taper angle  $\varphi = 15^\circ + 15^\circ = 30^\circ$



**Figure 12.** Dependencies of the equivalent stresses  $\sigma_{eqv}$  on the diameter  $D$  of the conical disk tool with the taper angle  $\varphi = 0^\circ + 30^\circ = 30^\circ$

Table 2 shows the polynomial dependencies of the equivalent stresses according to von Mises criterion  $\sigma_{eqv}$  on the diameter  $D$  of the disk tool in the plane of section over the V-flange edge on the part of the fixing screw of the mount to the prism for the coaxial rotation operation of four disk design options when cutting work faces.



Table 2. Polynomial dependencies of the equivalent stresses  $\sigma_{eqv}$  on the diameter D relating to four design options of twinned disk tools

Taper angles of disks $\varphi = \varphi_1 + \varphi_2$ , grad	Work faces, $\sigma_{compr}$ , MPa	Polynomial dependencies	Confidence coefficient of approximation $R^2$
25°+5°	12.4	$\sigma_{eqv} = 2E-07D^4 - 3E-05D^3 + 0.002D^2 - 0.0106D$	0.9711
	51	$\sigma_{eqv} = -8E-08D^4 + 1E-05D^3 + 0.0049D^2 - 0.0918D$	0.898
	60.6	$\sigma_{eqv} = -2E-07D^4 + 4E-05D^3 + 0.0025D^2 + 0.0038D$	0.8982
	78.9	$\sigma_{eqv} = -4E-07D^4 + 1E-04D^3 - 0.0005D^2 + 0.0579D$	0.9037
20°+10°	12.4	$\sigma_{eqv} = 1E-06D^4 - 0.0003D^3 + 0.0244D^2 - 0.5984D$	0.9399
	51	$\sigma_{eqv} = 1E-06D^4 - 0.0003D^3 + 0.0339D^2 - 0.7942D$	0.8921
	60.6	$\sigma_{eqv} = 1E-06D^4 - 0.0003D^3 + 0.0329D^2 - 0.7628D$	0.8877
	78.9	$\sigma_{eqv} = 9E-07D^4 - 0.0003D^3 + 0.0295D^2 - 0.6635D$	0.8909
15°+15°	12.4	$\sigma_{eqv} = 1E-06D^4 - 0.0003D^3 + 0.0247D^2 - 0.6035D$	0.9423
	51	$\sigma_{eqv} = 2E-06D^4 - 0.0006D^3 + 0.0517D^2 - 1.2264D$	0.858
	60.6	$\sigma_{eqv} = 2E-06D^4 - 0.0006D^3 + 0.0523D^2 - 1.1771D$	0.8458
	78.9	$\sigma_{eqv} = 2E-06D^4 - 0.0006D^3 + 0.0548D^2 - 1.2626D$	0.8041
0°+30°	12.4	$\sigma_{eqv} = -8E-07D^4 + 0.0003D^3 - 0.0246D^2 + 0.6791D$	0.9532
	51	$\sigma_{eqv} = -1E-06D^4 + 0.0004D^3 - 0.0355D^2 + 1.0052D$	0.9246
	60.6	$\sigma_{eqv} = -2E-06D^4 + 0.0005D^3 - 0.0405D^2 + 1.178D$	0.8986
	78.9	$\sigma_{eqv} = -2E-06D^4 + 0.0005D^3 - 0.037D^2 + 1.0852D$	0.8808

Figure 13 provides a summary graph to show the dependencies of the equivalent stresses  $\sigma_{eqv}$  on the diameter D of twinned disc tools having various designs held in the tetrahedral prism (three biconical with the following taper angles: 1 –  $\varphi = \varphi_1 + \varphi_2 = 25^\circ + 5^\circ = 30^\circ$ ; 2 –  $20^\circ + 10^\circ = 30^\circ$ ; 3 –  $15^\circ + 15^\circ = 30^\circ$  and one conical 4 –  $\varphi = 0^\circ + 30^\circ$ ) when cutting coal faces in mine workings.

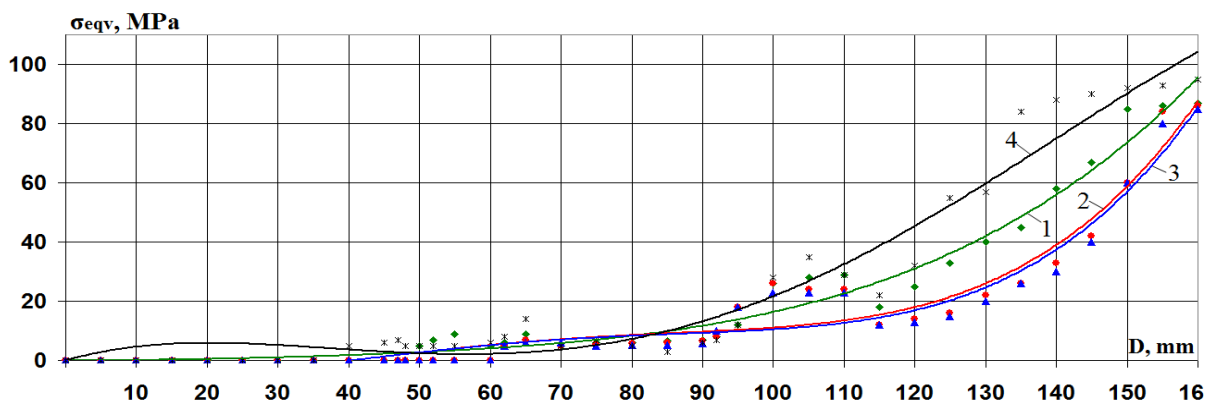


Figure 13. Dependencies of the equivalent stresses  $\sigma_{eqv}$  on the diameter D of disc tools having various designs when cutting a coal face  $\sigma_{compr} = 12.4$  MPa

The results of research and the technical solutions have been obtained in the framework of the government contract with the Ministry of Education and Science RF, project No. 632 "Investigating

parameters of technology and equipment for the choice and development of innovative technical solutions to improve operational efficiency of tunnelling and mining machines in Kuzbass".

## Conclusion

Analysis of the dependencies of the equivalent stresses  $\sigma_{eqv}$  on the diameter  $D$  in four various designs of the twinned disc tools shows that, when cutting coal faces in mine workings, all of the variants have behaviours in the form of polynomial dependencies with the maximum steepness growing towards the zone of cutting, with the depth of cutting  $h = 0.04$  m and the diameter of the disk V-flange  $D = 0.16$  m. The highest level of equivalent stresses  $\sigma_{eqv}$  is 95 MPa that is indicative for the cutting process in coal faces using the conical rotary tool  $\varphi = \varphi_1 + \varphi_2 = 0^\circ + 30^\circ$ . Relating to the three structural variants of biconical twinned disc tools ( $\varphi = \varphi_1 + \varphi_2 = 25^\circ + 5^\circ = 30^\circ$ ;  $20^\circ + 10^\circ = 30^\circ$ ;  $15^\circ + 15^\circ = 30^\circ$ ), the equivalent stresses  $\sigma_{eqv}$  are observed to reduce to 85-87 MPa.

It has been established that, when cutting rock masses, the dependencies of the equivalent stresses  $\sigma_{eqv}$  on the diameter  $D$  of the twinned disk tools also have a similar behaviour in the form of a polynomial dependencies with a flatter steepness towards the zone of cutting, compared to the cutting of coal faces, with the depth of cutting  $h = 0.006$  m and the diameter of the disk V-flange  $D = 0.16$  m. In this case, the maximum level of equivalent stresses  $\sigma_{eqv}$  for all variants of disk tools is within the range 97-100 MPa.

In general, the trends relating to the stress state of the mounting elements that hold the twinned disk tools, when cutting both coal and rock, are characterized by the following:

- When biconical disk tools are used for cutting, the polynomial dependencies of the equivalent stresses  $\sigma_{eqv}$  on the diameter  $D$  of discs are flattening with asymmetry parameters ( $\varphi = 25^\circ + 5^\circ = 30^\circ$ ;  $20^\circ + 10^\circ = 30^\circ$ ) changing into symmetry parameters ( $15^\circ + 15^\circ = 30^\circ$ ) in the area of cutting.
- When conical disk tools are used ( $\varphi = 0^\circ + 30^\circ$ ), the maximum steepness growing is observed with respect to the polynomial dependencies compared to the biconical disk tools of diameters close to the area of cutting;

Thus, implementing the proposed technical solution, relating to the mounting elements of disk cutting tools held in tetrahedral prisms to ensure the mode of simultaneous rotation, allows the scope of application to extend and the operational efficiency to enhance when using boom-type selective roadheaders, made in Russia and abroad, with cutting heads having two axial cutting drums in coal mining and rock excavating operations.

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