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RESEARCH OF THE STRESS-STRAIN STATE OF THE ROCK IN CONTACT WITH THE ELEMENTS OF THE DRILL BIT DURING DRILLING

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Abstract: *Research of the interaction of rock-cutting tools with rock with various approaches is presented in the article. In contrast to analytical and experimental methods with their limited and costly applicability, it is proposed to use numerical modeling to better represent the mechanics of rock destruction, to visualize the stages of destruction in a short time and in a cheaper way. This article allows to get an idea that using the finite element method can get mathematical modeling of plastic deformation, assess the stress-strain state of the bit and optimize the structural elements and working conditions of the rock cutting tool, analyze the dynamics of fracture forces and others. The dynamic interaction of the drill bit with the rock in case of two cones with different arrangement of buttons on one crown is investigated. In the process of analysis, it was found that the interaction of paired buttons with rocks has a force action on the area of the rock as well as the cone of the industry bit, but in a more intensively fluctuating way, by also saving energy. Advantageously, the arrangement of the buttons in pairs has not only tensile stress in the longitudinal direction, but also in the transverse direction, contributing to a wide coverage of the fracture zone.*

Keywords**:** *drilling, rock, finite element method, drill bit, numerical modeling, dynamics of buttons, rock destruction, rock-bit interaction.*

Introduction.

An open-pit mining method is predominantly the prevalent type of extraction worldwide due to its safety, ease and controllability relative to the underground method.

Drilling and blasting in opencast mining, due to its high cost and laboriousness, is one of the main production processes. Reducing the cost of drilling during open pit mining can reduce costs from the total cost of ore extraction to half. Therefore, scientists have always set themselves a task of increasing productivity and reducing production costs by examining a whole cycle of drilling and blasting processes. Optimization of the drilling and blasting process can be achieved through use of improved, more efficient drill bits, a rational choice of their types and a more advanced technology for their use in specified mining conditions.

An analysis of drilling and blasting and peculiarly the work of rock cutting tools show that the pace of development of the technology of drill bits due to the use of new materials, types and designs of bits has never stopped, but rather led to a constant increase in the level of penetration into the depth of the well and the life of the bits.

With the development of new quarries and the consequent increase in the volume of drilling operations, the complication of rock destruction conditions, the need for rock cutting tools of various types is at a tremendous pace. This leads to the need to optimize the parameters of drill bits, drilling modes in the shortest possible time. The only quick solution to such complex problems today can be the design of rock cutting tools using modern modeling methods.

Drill bit design encompasses many factors that must be considered in the early stages. One of the key factors is the interaction of the elements of the rock cutting tool with the rock. For the purpose of studying this process, scientists use various methods, including field experiments [1], laboratory tests [2-3], and numerical simulations [4-5].
Meeting the needs arising from the globalization of production activities of local large mining enterprises and changing market requirements contributes to urgent and effective product development decisions. The use of numerical modeling in the development of rock cutting tools is a reliable method to meet such needs.
The development of new roller cone and combined types of rock cutting elements of roller cone bits is a highly relevant scientific task, with the increasing volumes of roller cone drilling [6].
Studying the process of drilling rocks by crashing requires the interaction of the tool with the rock, the destruction of the rock and the formation of fragments. The process is influenced by parameters such as the properties of the destructive tool, the cutting mechanism and the properties of the rock. According to the authors [7], at sufficiently small depths of the wells, the dynamics of buttons is the basis for the dynamics of drill bits. And as a result, the attention of researchers is mainly focused on the search for functional relationships between the physical mechanical properties of rocks and the dynamics of buttons. In contrast to analytical and experimental methods with their limited or costly applicability, numerical modeling allows one to get a better idea of the mechanics of cutting rocks, step-by-step visualization of the stages of destruction in a short time and cheaper way.

Materials and methods.

In this study, the numerical research method was mainly used, including the analysis of the stress-strain state rock in the interaction with one cone of a tricone bita. An engineering software program ANSYS based on the Finite Element Method is used as the main tool of this work that can provide reasonable estimates of contact strength and can reflect the corresponding fragmentation and step-by-step progress.

Finite element method.

From a geotechnological point of view, the finite element method is considered as one of the powerful mathematical methods that exists today to solve fundamental problems. According to [8], any type of soil condition can be modeled using the finite element method. A complex soil profile is shown in Figure 1. The nodes in each of the finite elements are assigned soil properties of this layer, such as ϕ, γ (density), cohesion, the value of the standard penetration test (N), etc.

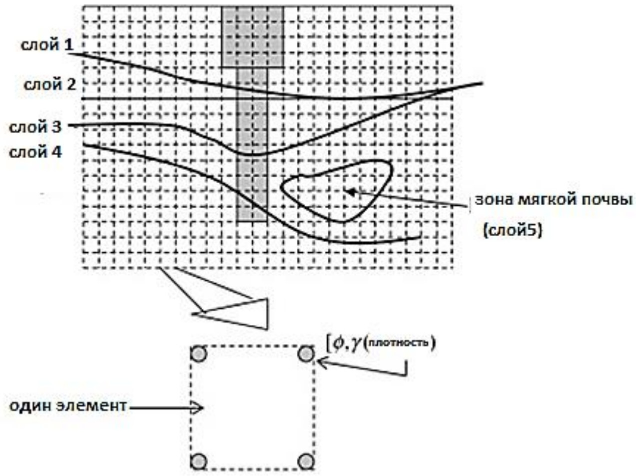

Figure 1. Finite element grid.

The goal of using the finite element method is to create a computer model of the material or structure for analysis and obtaining specific results. Practice shows that the analysis of the finite element method can be used to refine existing or new production processes. Manufacturers of various mining equipment can check the proposed model to meet the end-user specifications depending on the purpose and place of use of the tools, thereby saving time and development resources. And if the equipment fails, the FEM program is very useful to help the technician change the design in accordance with the given condition. Most importantly, using this analytic method, I predict failure due to unknown stresses, showing problem areas on the object and allowing designers to see all the theoretical stresses inside. In particular, this method for manufacturers of rock cutting tools makes it possible to represent the entire cycle of drilling processes that cannot be seen at the bottom of a well in field experiments or laboratory conditions when drilling rocks of various strengths. Mathematical modeling of plastic deformation, assessment of the stress-strain state of the rock and buttons of the bit, optimization of structural elements and working conditions of the rock cutting tool, prediction of residual stresses in the treated surface, analysis of the dynamics of cutting forces and others can be realized using the finite element method.

Research approaches to solving the problem of interaction.

Nowadays, everyone knows how complicated the process of drilling and rock destruction in the bottom of the well is, and they realize how important the constructive model of the rock cutting tool plays in this [11]. Scientists approach the issue of creating more efficient drill bits in various ways and study all kinds of solutions to the interaction problem and their consequences.

The deformation of the studied material can be described in various formulations. The choice of a specific approach is especially important, since the elements of the rock-cutting tool cause significant deformation in rocks during rolling. Scientists [9, 10] chose the Euler method to bypass potential grid distortion by moving material through a fixed grid in space to a stationary cutter. This approach is applicable especially for metal cutting, but has limited capabilities in the destruction of rocks.

There is another approach to studying the deformation of a material in interaction with another material. The Lagrange method allows one to obtain deformed geometry after each time step and visualizes the removal (erosion) of rock fragments in contact with the rock cutting tool. In order for the element erosion not to bring the rigidity matrix to unity, it is necessary to apply the explicit dynamics scheme for the solution.

Many research activities were carried out to analyze the model of the interaction of one cutter with a rock or a whole PDC (polycrystalline diamond compact) bit with rock using the Euler and Lagrange methods, as well as their combined formulation in solving problems of detecting rock deformation. Numerical simulation experiments were carried out using various loads, cutting tool speeds, PDC bit tilt angles, cutting areas and rock properties. The experimental results were analyzed using multiple nonlinear regression methods, and new models of the interaction of the cutting tool with the rock were proposed many times.

Analysis of the explicit dynamics of the bit-rock interaction.

The analysis of the interaction process of the elements of the drill bit with the rock is a difficult task. The process of destruction of the rock occurs when the cutter of the rock cutting tool during percussive-rotary drilling transfer mechanical energy to the surface of the rock and break it into pieces (fractures). Despite the fact that the finite element method was used to analyze a variety of engineering problems, it lacked the necessary basis for the reliable solution of problems associated with the destruction of rocks. The reason why the necessary basis for reliable problem solving was not enough is explained by the authors of [12] by the fact that from the point of view of modeling rock destruction, a number of difficult problems arise: first, the contact problem arises when the cutter advances and interacts with the surface of the rock. This is accompanied by the problem of determining when and if the rock experiences destruction. And if it does experience destruction, the scientist subsequently faces the problem of how to start and continue the fragmentation process. Then this sequence of problems is repeated at each stage of the journey until the destruction is complete. This sequence can be investigated using the explicit dynamics method used by many modern engineering programs.

Ansys allows one to analyze a computer model using various analysis options. For example, it contains static analysis, transient analysis, dynamic analysis, and others. Explicit Dynamics is one of the features of finite element analysis in Ansys. Short events physics for materials and structures that undergo very nonlinear, dynamic transitions can be shown using the Ansys explicit dynamics. Algorithms based on the first principles accurately predict reactions, such as large material deformations and fractures, as well as interactions between bodies and liquids with rapidly changing surfaces [13]. Specialized, accurate, and easy-to-use explicit dynamics tools have been designed to provide maximum performance at the design stage. Using ANSYS Explicit Dynamics products, scientists are able to investigate how the structure or its individual elements react to severe loads in a short time and optimize the design of any type of drilling tool. The explicit dynamics approach is especially relevant, given the high prices and valuable time for experiments and materials for the production of drill bits.

A study of the interaction of a cone of the tricone industry bit with a rock in ANSYS Explicit Dynamics.

The assembly of one cone of a tricone drill bit, now used in industry, was created in the Solidworks software program. The model developed for the analysis process is shown in Figure 2. The parameters of the crowns and buttons of one cone, as well as the rock, in our case limestone, which is often found in quarries, are shown in Table 1. Such parameters as tensile strength under compression and tension, Young's modulus and Poisson's ratio, which are necessary for analysis, are given in the database of the ANSYS program (Engineering data sources - Geomechanical materials - Limestone). On the Protodyakonov scale, this rock has an indicator of strength f – 8: 10. Despite the fact that the rocks are not naturally homogeneous, limestone was considered homogeneous to idealize the drilling process, because the uniformity of the material guarantees a sufficiently low dispersion of measurements.

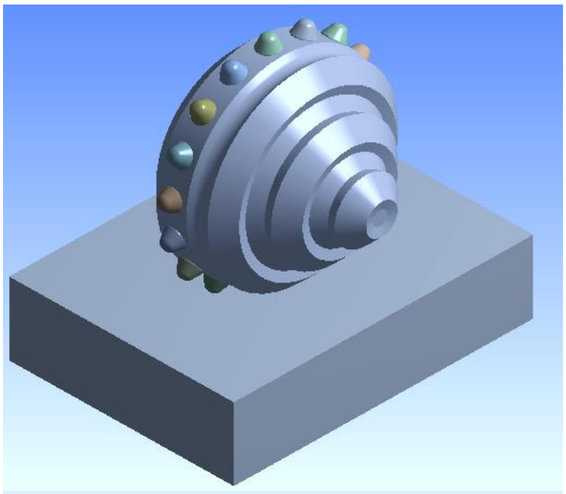

Fig. 2: Assembly model of one crown of cone and rock

The process of finite element analysis of the interaction of the elements of the cone with the rock in the ANSYS program is as follows:

Create and convert the developed model from a CAD program to ANSYS

Set up cone, buttons and rock parameters in the engineering data of the program. With the development of research in the field of mechanical fragmentation of a rock, a group of scientists [14] of modern society came to a conclusion that the physical and mechanical properties of the rock, such as Young's modulus, compressive strength and tensile strength, are the dominant parameters affecting the penetration process during rock drilling.

Table 1.

Name	**Cone**	**Buttons**	**Rock**
Qty	1	17	1
The form	Conical	Vaulted buttons	Quadrangular
Material	Structural steel	Tungsten carbide	Limestone
Density	15600 kg m-3	7850 kg m-3	2700 kg m-3
Tensile strength	4.6 E + 08 Pa	4.45E + 08 Pa	4.0e + 06 Pa
Young's modulus	2E + 11 Pa	6.34 E + 11Pa	3.7845E + 10 Pa
Poisson's ratio	0.3	0.21	0.3077

Create a mesh for each element of the model. In the process of engineering modeling, to simplify the calculation, users are provided with Euler and Lagrange methods that allow breaking model geometries into simple elements. In the analysis, such a breakdown can be used as discrete local approximations of a larger region of the studied objects. Since meshing affects the accuracy, convergence, and simulation speed, the right choice of mesh is of great importance. Mesh construction usually takes a significant part of the time required to obtain the results of the analysis, therefore, to obtain a faster solution, it is necessary to use automated instruments of combination. Despite the fact that an automated mesh makes it possible to obtain a quick solution, for a more accurate analysis it is necessary to use an improved mesh on the contact area between the cone and the rock. Details of the mesh settings for the studied models are shown next to the object of Figure 3.

Settings	**Unit**
Mesh	8 mm
Refinement	2
Nodes	34654.
Elements	169010.

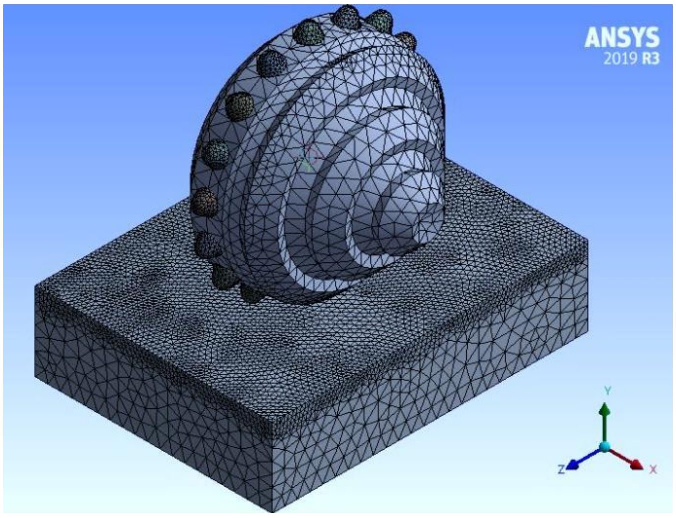

Fig.3. Mesh Settings of the cone and rock

Setting boundary conditions. In order to avoid errors in the simulation during interaction, the rock is fixed on the sides so that it does not move during contact (Figure 4).

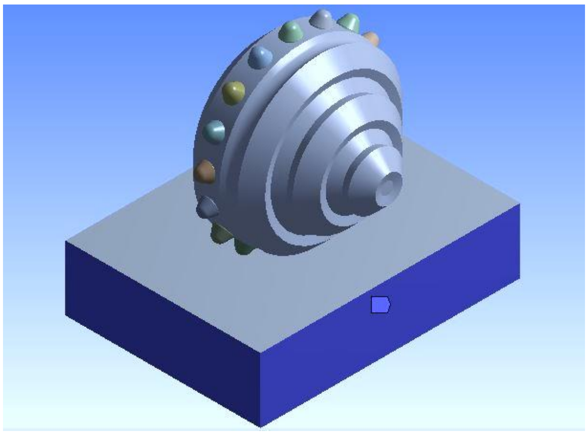

Fig. 4. Model with fixed rock sides

Setting up the initial conditions. The duration of the explicit dynamic analysis is very short, so variables such as temperature and pressure can be neglected for this study. For rotating over the surface of the rock and destruction, it is necessary to apply the angular velocity to the cone with buttons, for this case, the indicator of this parameter is 100 rpm. The direction of angular velocity is fixed clockwise and leads to contact with the rock. Axial load value is 30kN and analysis time 4 milliseconds.

The simulation starts after the data input for analysis has been completed. Equivalent (von Mises) stress was chosen for this study to represent the dynamic stress-strain state of the model.

A study of the bit-rock interaction of the industry cone.

The simulation analysis process took about 10 hours. The destruction of the rock occurred due to the penetration, that is, the percussive-rotary action of the cone buttons into the rock (Figure 5). Fragmentation can be observed after the solution is reached, when the buttons penetrate into the rock and, having lost its structural structure, it begins to collapse. The behavior of the cone and the buttons of the industry bit on the scale of equivalent tensile stress shows the results, which are shown in table 2 and a linear graph (figure 6).

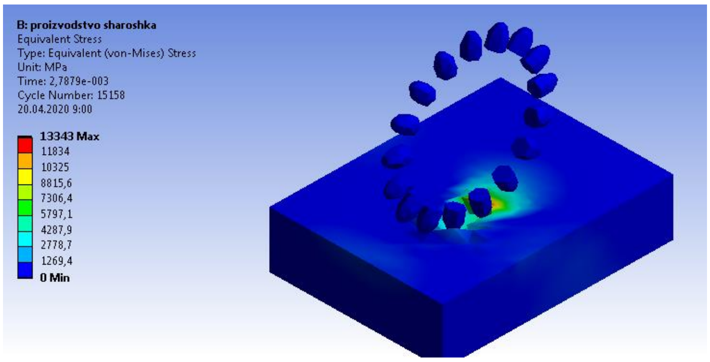

Fig. 5. Equivalent stress in the contact zone of the cone buttons of the industry bit with the rock

Table 2. Equivalent stress scales in the contact zone of the cone buttons of the industry bit with the rock

Time [s]	Maximum [MPa]	Average [MPa]
2,e-004	1766	215
1,e-003	1481	185
2,e-003	7392	246
3,e-003	13343	354
4,e-003	5488	308

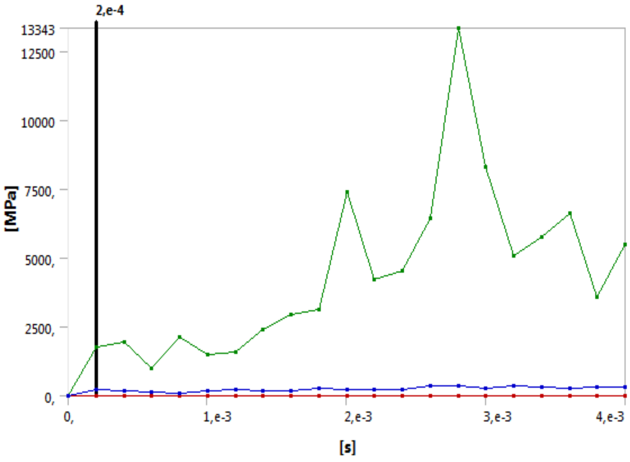

Fig. 6. Scheme of change of equivalent rock stress by penetration of cone elements into it

The magnitude and direction of stresses in the areas of contact of the buttons with the rock, which determine the stress-strain state of the rock and cone (Fig. 5.), are described by the color scale on the left side of the program desktop. The color scheme depicts the presence of compressive forces in the contact zone (negative values) and tensile forces (positive values).

From Fig. 5. one can see that when the buttons of the cone of industry bit penetrate the rock, tensile forces in the longitudinal direction of the rock can be observed. The yellow and red colors on the surface of the rock mean that the rock in these zones is stressed and loses its structure, which contributes to the destruction of this part of the rock. The blue color on the scale indicates that that zone of the rock is less stressed and there is not enough force to destroy it.

The graphic (Fig. 6) shows how the equivalent stress reaches a peak in the third millisecond, signaling that the maximum tensile stress occurs at the initial point of contact of the buttons in rotational movements with the rock (moment of button eating into the rock). In general, it can be seen from Table 2 and the graph (Fig. 6) that the equivalent stress (or von Mises stress) tends to fluctuate in the first milliseconds with increasing values. Peak stress is reached in the third millisecond with a value of 13343 MPa, when the cone buttons under axial load and percussive-rotary movement destroy the contact part of the rock. The red color on the contact part between the button and the rock shows where the main fragmentation process occurs. The oscillation of the equivalent stress continues after reaching the peak, but in a more intense way.

A study of the interaction of the paired cone buttons of an experimental bit with rock.

Similar settings and conditions are applied for analysis of the interaction of the paired cone buttons of an experimental bit with rock as for the cone buttons of the industry bit. After initial and general conditions set, the program gives a solution to the given parameters. The following are the results of the simulation.

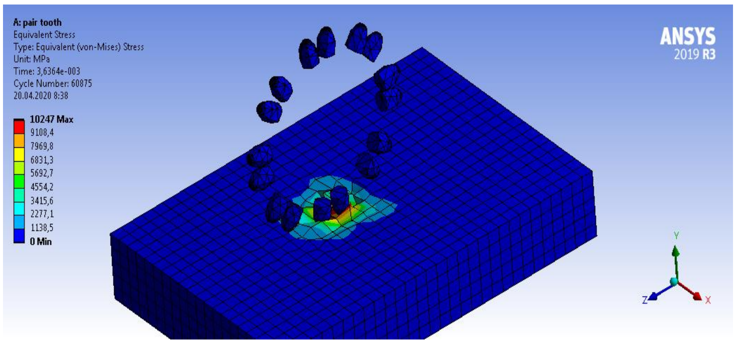

Fig. 7. Equivalent stress in the contact zone of the paired cone buttons of the experimental bit with the rock

Table 3. Equivalent stress scale in the contact zone of the paired cone buttons of the experimental bit with the rock

Time [s]	Maximum [MPa]	Average [MPa]
2,e-004	4098	382
1,e-003	4177	401
2,e-003	1763	198
3,e-003	9746	440
4,e-003	5216	413

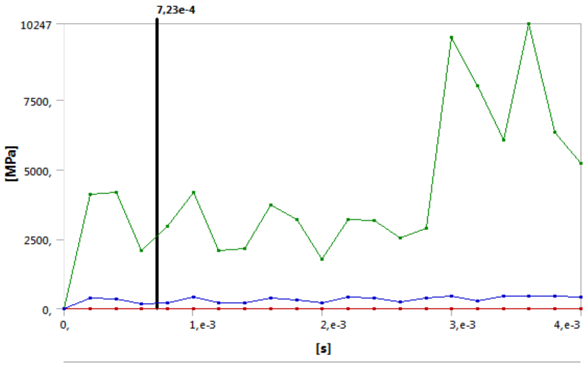

Fig. 8. Scheme of change of equivalent rock stress by penetration of paired cone buttons into it

An analysis of the interaction of paired buttons with rocks (Fig. 7) shows that cones with paired arrangement of buttons have actions on the area of the rock as cones of a industry bit, but in a more intense fluctuating way.

Unlike the cone of the industry bit, the buttons with a pair allocation do not have only tensile stress in the longitudinal directions, but also there is impact in the transverse direction, which speaks of a wide capture of the contact zone of rock destruction.

Since we are considering the effect of the allocation of the buttons relative to the destruction of the rock, it is necessary to study what stress is required for the plastic deformation of the rock body. The arithmetic average of the maximum equivalent stress (von Mises stress) for simulation of a cone with a paired buttons is 4395 MPa, whereas the value of the arithmetic mean sum of the maximum Mises stress for a cone of an industrial bit depicts 4463 MPa. But if we consider the arithmetic mean value of the average tensile force Fig. 5 and table 1 show that in cones with paired buttons it is much larger than in field ones, 340 MPa and 245 MPa, respectively. Figure 5 presents that the peak values of tensile stress or Mises stresses in the two simulations differ significantly, that is, 10247 MPa with the participation of paired buttons and 13343 MPa with normal buttons.

Results and Discussion

In general, a cone with a "paired buttons" acts on the cross-sectional area of the rock with values less than the buttons of the industry bit, which naturally affects the energy efficiency of the bit. The arrangement of the buttons in pairs does not only have tensile stress in the longitudinal directions, but it affects in the transverse direction as well, contributing to a wide coverage of the fracture zone. The oscillatory values of the equivalent stress on the graphs signal the dynamic movements of the cone and the progressive contact of each button with the rock.

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