Increasing the content of coarse fractions in the mined coal mass by a combine using paired cuts

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Abstract. The main volume of coal is mined underground using shearsers. In modern shearsers, auger actuators are mainly used, which are distinguished by the simplicity of design, manufacturability and reliability. However, in the process of separating coal from mass by cutting, the yield of fine grades is 40-50 % of the total production volume. Therefore, the search and development of technical solutions that provide an increase in the yield of large fractions in the process of coal mining with auger shearsers is an urgent task. Traditionally, this problem is solved by increasing the thickness of the slices, which is achieved by installing cutters with a larger radial reach and increasing the shearer feed rate. An unconventional way to increase the cross section of slices by forming energy-efficient paired and group slices with mutual superposition of stress fields in the mass from the action of neighboring cutters is considered. The results of modeling the process of cutting coal confirm that an increase in the efficiency of destruction of the rock mass by the cutters of the auger executive bodies of the shearer can be achieved by a complex technical solution, including the formation of paired cuts and combined stress zones in the rock mass. As a result, the output of large fragments when cutting with paired cutters increases by 1.3-1.8 times compared with cutting with a single cutter.

Keywords: coal; mass; mining; harvester; cutter; cutting; force; stress; modeling

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Introduction. In the process of mining by modern mining machines, the extracted mass contains more than 40 % of fine grades and dust, which significantly increases the loss of coal, energy costs and labor costs for sedimentation, binding and removal of dust, and reduces the safety of mining operations. Shearsers in the process of mining separate the mineral from the mass with cutters, which are one of the main groups of mining working tools [1-3]. The cutters operating modes determine the intensity and efficiency of the entire technological chain of mining at a mining enterprise [4-6]. The mass of the cutter is no more than a thousandth of a mining machine [7-9], but at the same time it is its main element, since its hardness, wear resistance and failure-free operation determine the efficiency and reliability of any downhole mining machine [10-12].

The correct choice of the cutting tool, its placement and fastening schemes on the executive body determine the shape and cross-sectional area of any cut, which significantly affects the productivity of the mining machine, the granulometric composition of the mined coal and the specific energy consumption [13-15].

Formulation of problem. The values of the phase parameters of elementary spalls, as elements of the cutting process, are significantly affected by the conditions for the stress zones formation in the near close-to-cutters space of the mass, in particular, the superposition of stresses from the action of neighboring cutters of the executive body, which is not taken into account in modern calculation methods. This limits the possibilities of forming new more energy-efficient types of slices, large-
scale cleavage executives and high-performance shearsers [16-18]. The use of paired and group cuts makes it possible to reduce the energy intensity of coal separation from the massif, improve its quality in terms of particle size distribution and develop sequential-group schemes for arranging cutters that create combined stress zones in the rock mass.

**Methodology.** Of the known models of destructive strain of coals, the most suitable is the Johnson – Cook model, which takes into account kinetic hardening and adiabatic heating of the deformable material [19-21]. Therefore, using the Johnson-Cook model, one should evaluate the destructibility of coals, thereby comparing it with the results of experiments. The development of reliable and accurate methods for estimating the values of the cutting forces of rocks and coals is one of the priority areas of scientific research [22-24].

To study the features of the coal destruction process, the ABAQUS software and the Johnson-Cook model were used. The objectives of simulation are to identify the patterns of formation of the stress area in the near-cutting zone of the destroyed massif and to assess the possibility of purposeful control of cutting parameters according to the Johnson – Cook model [25, 26]. The simulation allows you to test the Johnson – Cook criteria and the characteristics of chip formation, cutting forces, stress and strain. The correlation of cutting parameters and stress is realized by simulation. Stress theory (maximum strain energy theory) has been applied to determine the maximum stress during turning under various cutting conditions [27-29].

The theory of highest stresses suggests that the yield strength of plastic materials begins when the stress reaches a critical level [30, 31]. It is believed that the separation of coal from the rock mass in time proceeds similarly to the mechanical processing operation of various materials. The process simulation was carried out by the finite element method in the ABAQUS/Explicit software package. In the adopted model, the stress during plastic strain is determined by the formula [32-34]:

\[
\sigma = (A + Be_p^n)(1 + C \ln \left( \frac{\varepsilon}{\varepsilon_0} \right)) ,
\]

where \(\varepsilon_p\) – effective plastic strain; \(A, B, N, \varepsilon_0\) – model parameters; \(n\) – strain hardening index; \(C\) – strain coefficient. The prime means the derivative with respect to time. The formula is a curve of coal strain.

According to research results [27, 33] parameters of the coal model are determined through experiments and formulas: density \(\rho = 1352\) kg m\(^{-3}\); shear modulus \(G = 0.58\) GPa; constant damage \(D_1 = 0.027\); damage constant \(D_2 = 1\); normalized cohesive strength \(A = 0.4\); normalized hardening factor under pressure \(B = 0.7\); strain coefficient \(C = 0.05\); hardening index under pressure \(N = 0.5\); principal fracture stress \(\sigma_{\text{max}} = 10\) MPa; strain hardening index \(n = 0.31\).

A 3D model of a coal mass 80×50×20 mm with a cut thickness \(h = 2\) mm was built (Fig.1). The cutter is fixed in a vertical position, it is given speed in a horizontal direction parallel to the initial upper surface of the mass. In the models of the cutting process, the cutting speed \(v_c = 0.08\) m/s, the coefficient of friction between the cutter and the mass \(\mu = 0.22\) are assumed. Friction coefficients in other friction pairs are taken equal to zero.

**Results.** When cutting coal, the stress in mass (Fig.2) is distributed in accordance with closed curves around the cutter without kinks: the closer to the cutter, the greater the stress in the mass.

![Fig.1. Boundary conditions of the coal mass model](image-url)
From the formula and Fig. 2, according to the simulation results, it follows that in the zone $c_i$ the value of the main fracture stress of coal $\sigma_{\text{max}} = 10 \text{ MPa}$. The stress zone width is greater than the width of the cutting edge of the cutter $b_c$ by 2.81 times.

The process of a single cut is represented (Fig. 3) by three zones:

- Zone I – cutting force steadily increases and $b_c$ reaches the maximum value $z = 16.5 \text{ kN}$;
- Zone II – stationary cutting mode: the cutting force changes from 16.5 to 11.5 kN with a constant value of the mathematical expectation estimations;
- Zone III – the force steadily decreases from $z = 16.4 \text{ kN}$ to zero.

The change in force in zone II adequately reflects the features of cutting coal with a single cutter and can be used to analyze stationary cutting conditions.

Similar to modeling with a single cutter, modeling of paired slices was carried out, which are installed without leading each other in parallel, close planes of rotation with a step $t_{cp} = 1.5b_c$ (Fig. 4).

Cutter pitch $t_{cp} = 1.5b_c$. Isolines of equal stresses in the mass when cutting coal with paired cutters (Fig. 5, a) are located in the form of closed curves around the cutter: the closer to the cutter, the greater the stress in the rock mass. In zone $c_i$, the stress value $\sigma_i = 11.52 \text{ MPa}$ greater than the value of the main fracture stress of coal $\sigma_{\text{max}} = 10 \text{ MPa}$. The width of the stress zone when cutting with paired cutters is greater than the width of the cutting edge of the cutter $b_c$ by 2.99 and 1.58 times when cutting with one cutter.

Cutter pitch $t_{cp} = 2.0b_c$. From Fig. 5, b it follows the results of coal cutting simulation: in the zone $c_i$, the stress value $\sigma_i = 11.74 \text{ MPa}$ is greater than the value of the main coal fracture stress $\sigma_{\text{max}} = 10 \text{ MPa}$.

The width of the stress zone is 4.6 times greater than the width of the cutting edge of the cutter $b_c$ and 1.7 times when cutting with one cutter. The distribution lines of equal stresses are continuous seamless curves, but small wrinkles appear. The stresses in these places exceed the maximum yield strength of the material. Looking at the distribution of stresses, the cutters work effectively by supporting each other and have proven to be more efficient than when cutting with cutter pitches $t_{cp} = 1.5b_c$. 
Cutter pitch \( t_{cp} = 2.5b_c \). It follows from the results of coal cutting modeling that the stress value \( \sigma_i = 11.53 \text{ MPa} \) (Fig. 5, c) is greater than the value of the main coal fracture stress \( \sigma_{max} = 10 \text{ MPa} \). At the same time, the width of the stress zone is 2.65 times greater than the width of the cutting edge of the cutter \( b_c \) and 0.95 times less than when cutting with one cutter. The general curve, reflecting the distribution of stresses in the mass between two cutters, is characterized by the presence of cracks and stresses in these positions, which are less than the critical stress of the material. Thus, when the cutting paired incisors are located with the installation step \( t_{cp} = 2.5b_c \), they do not support each other. The size of fragments of destruction particles is much smaller when cutting with paired cutters with a cutting step of 1.5; 2.0 \( b_c \). In a small stress zone between two cutters, smaller chips are formed, which increases energy consumption and reduces the efficiency of the process.

The length of single and paired cuts practically does not change in the direction of the cutting speed. In the process of a paired cut, the conjugated stress distribution zones with characteristic lines of closed arcs are formed in the mass. In Fig. 5, a, b, the stress zones are united by isolines of equal stresses, which creates conditions for the formation of larger chips. Between adjacent conjugated stress zones, regions are formed that cause the appearance of small chips. In the steady cutting mode, different from the reference one (with a constant cut thickness \( h = 3 \text{ mm} \)), the effective cutting forces and specific energy consumption depend not only on the cutting resistance and the degree of fragility of the mass, but also on the cutting conditions. Therefore, the definition of cutting forces is based on the value of the specific cutting energy in the reference mode.
Results discussion. The processes of paired cuts with different steps of setting the incisors have the following zones (Fig. 6):

- zone I – cutting forces steadily increase and reach maximum values: at $t_c = 1.5$; 2.0; 2.5$b_c$ forces reach values $z = 13.9$; 13.0; 20.1 kN respectively;
- zone II – stationary cutting mode: at $t_c = 1.5$; 2.0; 2.5$b_c$ cutting forces change from 13.9 to 15.2; from 13.0 to 15.5; from 10.1 to 15.5 kN, respectively. At the same time, the values of estimates of the mathematical expectation remain unchanged;
- zone III – at $t_c = 1.5$; 2.0; 2.5$b_c$ cutting force from values $z = 15.2$; 15.5; 15.5 kN respectively reduced to zero.

From Fig. 6 it can be seen that the forces during cutting with paired cutters with cutter installation steps $t_c = 1.5$; 2.0$b_c$ less than when cutting with $t_c = 2.5b_c$.

From Figs. 3 and 6 it follows that when cutting with paired cutters with a setting step $t_c = 2.0b_c$, the cutting forces are the smallest, and the width of the chip fragments is the largest. This confirms the presence of rational slices in terms of their effectiveness and the possibility of choosing the values of the parameters of paired slices in comparison with single and group slices.

Conclusion. Based on the results of coal cutting simulation using ABAQUS software, the following conclusions can be drawn:

- in the process of separating coal from the mass by paired cuts, the yield of large fractions increases compared to a single cut;
- at $t_c = 2.0b_c$, fragments with the largest chipping area are formed;
- when using paired and group cuts, the formation of combined stress zones in the massif is possible, causing an increase in the size of chip fragments by 1.3-1.8 times;
- when cutting coal with paired cutters with $t_c = 2.0b_c$, the cutting forces on a single cutter are less than when cutting with a single cutter or paired cutters with $t_c = 1.5$; 2.5$b_c$;
- the proposed rational pair and group cuts in terms of shape and cross-sectional area provide the possibility of creating more energy-efficient sequential-group schemes for placing cutters on the auger executive bodies of shearsers.

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