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Yu. N. Linnik[1],
orcid.org/0000-0003-3968-0026,
V. Yu. Linnik[1],
orcid.org/0000-0001-5130-8222,
S. A. Prokopenko[2],
orcid.org/0000-0002-0141-5377,
A. Zich[3],
orcid.org/0000-0002-8171-0375

1 – Federal State Educational Institution of Higher Education "State University of Management", Moscow, Russian Federation, e-mail: vy_linnik@guu.ru
2 – National Research Tomsk Polytechnic University, Kemerovo, Russian Federation
3 – MS QF GmbH, Oderwitz, Federal Republic of Germany

FORMATION MECHANISMS OF MAXIMAL LOADS ON CUTTERS AND CUTTING HEADS OF COAL MINING MACHINES

Purpose. To determine an influence exerted by the cutting mode and by geometry of cutters on the impact loads in various scenarios of cutter–solid inclusion interaction.

Methodology. Mathematical simulation, statistical analysis

Findings. Fracture of coal seams of a complex structure which contain solid discontinuities (solid inclusions and hard dirt bands) is associated with generation of impact loads on cutters and cutting heads of mining machines which cause a decrease in the productivity of the coal extraction process and premature failure of their components and elements. This impairs efficiency of coal cutting and causes premature failure of different components and parts. It is found that when a cutter cuts an inclusion or touches it, the size of the inclusion has no influence on the value of the peak load. On the contrary, in case of tear-out of an inclusion, the peak cutting force value essentially depends on the size and shape of the inclusion, as well as on the brittleness and plasticity of coal as these properties govern coal-inclusion cohesion. It is found that out of all modes of cutter-solid inclusion interaction, the highest loads arise in the mode of central cutting of inclusions. The mechanisms and behavior of occurrence of loads in short-term cutting of large (unbroken) solid inclusions by a group of cutters are discussed. The maximal loads on groups of cutters on cutting heads can also arise in gradual stalling when the average loading level approaches the tractive effort torque of electric motor when a group of cutters cuts many solid inclusions simultaneously, or in undermining of roof rocks, or in cutting hard dirt bands.

Originality. The probabilities of solid inclusion cutting by a cutter are determined for different outputs of a cutting head, and the action times of the maximal peak load in cutting a coal strip 100 m long are assessed. The relations are proposed to calculate the levels and action times of maximal loads on a group of cutters in cutting solid inclusions, as well as the coefficients of variation in the loads and the loading inequality of a cutting head.

Practical value. The results obtained by the authors should be taken as a basis in determination of the maximal instantaneous torque in the cutting head transmission to be used later on in calculation of the long-term strength of the transmission components.

Keywords: *coal, cutter, cutting head, coal mining machine, solid inclusions, cutting force, cuttability*

Introduction. Cutting of complex structure coal seams is associated with high loads applied to cutters of cutter–loaders, which results in premature failure of different assemblies and components of mining machines. The knowledge of maximal load patterns and values is important for the first turn for the stress analysis of transmission components which transmit loads to cutting heads and cutting tools of coal mining machines. The maximal loads are generated, as a rule, on cutters in cutting large and solid inclusions (carbonate, carbonate–pyrite and pyrite) which are much stronger than coal.

Literature review. Cuttability of complex structure coal seams and maximal loads on cutters of mining machines in interaction with solid inclusions and hard dirt interbeds were studied by many researchers both in Russia and abroad. For example, I. Albul jointly with V. Melamed found that peak maximal loads arose in cutting tightly embedded (conditionally) inclusions in coal, when inclusion–coal cohesion is higher than cohesion between coal particles. Nevertheless, the mechanism of maximal loading of a cutter in contact with large and solid inclusions has been poorly studied, and the currently existing methods for computation of such loads neglect some influencing factors. In this connection, studies were carried out to study the mechanisms of destruction and interaction of cutters with solid inclusions and to develop on this basis the calculated dependences of the maximum loads as a function of the geometric parameters of the cutting tool and cutting modes, as well as the impact of loads on the strength and durability limits of the transmission elements of cleaning combines.

Results. Maximal loads on cutter. The full-size tests simulating cutting of a coal/cement block containing inclusions of various size and strength revealed five representative modes of cutter – inclusion interaction and the associated relative values of maximal loads (Table 1). The relative maximal loads were evaluated with the deduction of forces generated on the cutter in cutting the coal/cement block without any contact with solid inclusions, and the cutting force in cutting an inclusion through its center (hereinafter, central cutting) was assumed to equal one.

It is found that in the modes of cutting and touch, the size of an inclusion has no influence on the value of the peak force on the cutter. In case of tear-out, the peak cutting force greatly

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Table 1

Maximal loads on a cutter in different modes of interaction with solid inclusions

Cutter–inclusion interaction mode	Relative maximal load on cutter
Central cutting	1.0
Edge cutting	0.2–0.9
Touch	0.1–0.2
Tear-out	0.3–0.1
Drawing-out	0

depends on the size and shape of an inclusion, as well as on the brittleness and plasticity of coal, which govern the nature of the inclusion and coal cohesion. The maximal load in tear-down is not higher than the force generated in the central cutting as the latter takes place when tear-out is impossible. For example, the cutting tests of solid carbonate inclusions in a viscous coal/cement block with cuttability A = 200 N/mm using sharp and blunt radial cutters with prismatic cutting edge show that: the average cutting force Z_{sharp} = 1.8 kN with the sharp cutter and Z = 3.0 kN with the blunt cutter; the average feed force Y_{sharp} = = 0.9 kN with the sharp cutter and Y = 3.2 with the blunt cutter; the peak cutting force Z_{peak} = 55 kN and the average peak cutting force $\overline{Z}_{peak} = 33\text{ kN}$; the peak feed force Y_{peak} = 15 kN and the average peak feed force $\overline{Y}_{peak} = 11\,kN$. From the comparison, the maximal forces of cutting and feed in cutting a solid inclusion are 10–30 times higher than the average forces.

Quantification of maximal loads was performed for the cases of central cutting of carbonate inclusions with a sharp cutter

$$\begin{aligned} Z_{peak} &= Z_{peak.ref} k_{w_z} k_{a_z} k_{V_z} k_{m_z};\\ \overline{Z}_{peak} &= \overline{Z}_{peak.ref} k_{w_z} k_{a_z} k_{V_z} k_{m_z};\\ Y_{peak} &= Y_{peak.ref} k_{w_y} k_{V_y} k_{rf_y};\\ \overline{Y}_{peak} &= \overline{Y}_{peak.ref} k_{w_y} k_{V_y} k_{rf_y}. \end{aligned} \tag{1}$$

For the stable point-to-point cutting mode with a reference cutter (cutter width w = 2 cm, cutting angle a = 50°, straight cutting edge), the relations to find the maximal and average peak cutting forces are

$$\begin{aligned} Z_{peak.ref} &= \frac{5200(1+3.36h)t}{t+1.8};\\ \overline{Z}_{peak.ref} &= \frac{5200(1+2h)t}{t+2.5};\\ Y_{peak.ref} &= \frac{2000(1+0.29h)t}{t+3.7};\\ \overline{Y}_{peak.ref} &= \frac{15\,700(1+0.26h)t}{t+3.4}. \end{aligned}$$

In the formulas above, $Z_{peak.ref}, \overline{Z}_{peak.ref}, Y_{peak.ref}, \overline{Y}_{peak.ref}$, are the maximal peak and average peak forces of cutting and feed on the reference cutter; h and t are the depth and width of cutting, respectively, cm; k_{w_z}, k_{w_y} are the influence coefficients of the cutter width on the maximal peak and average peak forces of cutting and feed, respectively; k_{a_z} is the influence coefficient of the cutting angle on the maximal peak and average peak cutting force; k_{V_z}, k_{V_y} are the influence coefficients of the V-shaped front face of the cutter on the maximal peak and average peak forces of cutting and feed, respectively; k_{m_z}, k_{rf_y} are the influence coefficients of the cutting mode and rear face shape of the cutter.

The experimental expressions to evaluate the coefficients $k_{w_z}, k_{w_y}, k_{a_z}, k_{V_z}$ and k_{V_y}, taking into account the influence of cutter geometry on the maximal loading for cutters different from the reference cutter are given by

$$\begin{aligned} k_{w_z} &= 0.5 + 0.25w;\\ k_{w_y} &= 0.3 + 0.35w;\\ k_{a_z} &= \left[\frac{0.7a}{150-a}\right] + 0.65; \end{aligned}$$

$$k_{V_z} = \frac{0.58(a_{wf} - 100)}{a_{wf} - 65} + 0.6; \tag{2}$$

$$k_{V_y} = 0.64 + 0.002a_{wf}, \tag{3}$$

where a_{wf} is the wedge angle of the front face of the cutter, deg.

Formulas (2, 3) are valid when 100° ≤ a_{wf} ≤ 180°. For cutters with an oval front face, k_{V_z} and k_{V_y} are calculated by the same formulas with a_{wf} = 150–160°.

The value of the cutting mode influence coefficient in the echelon pattern cutting is recommended to be taken as $k_{m_z} = 1.2$ in finding Z_{peak} and as $k_{m_z} = 1.1$ in finding $\overline{Z}_{peak}$. For the point-to-point cutting pattern, $k_{m_z} = 1$.

The values of k_{rf_y} are recommended to assume as 1, 0.85–0.9 and 0.6–0.7 for cutters with straight, oval and triangular front cutting edges, respectively.

The action times of the maximal peak and average peak forces in cutting of solid inclusions are determined from the expressions below:

- maximal peak force action time

$$t_{peak} = 1/100v_{cut};$$

- average peak force action time

$$T_{peak} = L/100v_{cut},$$

where l and L are the lengths of the cutter paths during the action times of the maximal peak and average peak forces, respectively, cm.

Maximal loads on cutting head. The maximal loads arise on the cutting head of a coal mining machine for a short time when a group of cutters cut large (unbroken) solid inclusion and hard dirt bands (sandstone, siltstone) which feature high density in complex structure coal seams.

The operating practice and bench-scale tests show that the maximal loads on a group of cutters on the cutting head arise in [2]:

- cutting of solid inclusions and hard dirt bands by one or a group of cutters;
- stalling when the average level of loading approaches the tractive effort torque of the motor in cutting large solid inclusions and hard dirt bands, or in roof rock undercutting.

These specific types of maximal loads should be taken as a basis in calculation of long-term strength of transmissions of cutter-loader cutting heads [2, 10, 11].

When a group of cutters cuts solid inclusions, the maximal loading is governed by the number of cutters which cut the inclusion simultaneously, and by the depth of cut. Table 2 gives the values of the total maximal loads on a group of cutters in arbitrary units for a limiting cut depth equal to radial overhang of a cutter ($h = l_{rad}$) and for an average cut depth $\overline{h} = l_{rad}/k$ (at k = 1.5–2).

From the bench-scale cutting tests of coal/cement block with embedded solid inclusions, it is calculated that probability of cutting an unbroken solid inclusion by a single cutter at a cut depth $h = l_{rad}$ (relative maximal load of 3.25) arises at the outputs of 150–200 kt. These conditions and the average peak loads $\overline{Z}_{peak}$ should be assumed as a basis in calculation of long-term strength of transmission. In case of the outputs over 500 kt, the loads should be assumed to have higher values. Regarding cutting tools, their long-term strengths should be calculated for outputs from 10 to 100 t at the peak cutting forces (Z_{peak}) in cutting solid inclusions at a cut depth $\overline{h} = l_{rad}/k$.

The action time $\sum t_{\max}$ of the maximal peak load in extraction of a coal strip 100 m long is given by (s)

Table 2

Relative level of total maximal loads

Operating conditions	Relative total maximal loads			
Number of cutters simultaneously cutting solid inclusions	1	2	3	4
Depth of cut $h = l_{rad}$ $\bar{h} = l_{rad}/k$	3.25 1	6.5 2	– 3	– 4

$$\sum t_{\max} = Nt_{peak}/(100v_{cut}),$$

where N is the number of solid inclusions in the extraction strip.

The action time of the average peak load under the condition above is calculated from the formula (s)

$$\sum T_{\max} = N_q T_{peak} = N_q L/100v_{cut}),$$

where N_q is the number of solid inclusions in the extraction strip.

It is experimentally found [15] that, subject to the size and specific content of solid inclusions in coal, the action times of the specified forces are: $\sum t_{\max} = 1–45$ s and $\sum T_{\max} = 15–210$ s.

The coefficient of variation in the average peak cutting force is given by

$$CV_{Z_{peak}} = (5000/\bar{Z}_{peak}) + 0.15. \quad (4)$$

The maximal peak cutting force on a cutter in cutting solid inclusions is

$$Z_{peak.\max} = \bar{Z}_{peak}(1 + 3CV_{Z_{peak}}). \quad (5)$$

Accordingly, the instantaneous torque on the cutting head transmission, whose value is used to calculate the long-term strength of transmission, is found from the formula

$$M_{p.\max} = Z_{peak.\max} D/2,$$

where D is the diameter of the executive body, m.

Actually, in operation of cutter–loaders, the number of cutters which simultaneously cut inclusions is less than the number of cutters which interact with coal. On this basis, the ratio of inequality of loading exerted on the cutting head is to be given by

$$IR = (n_1 - 1)\sqrt{n_1 + n_2(ir_2 - 1)^2(ir_1 - 1)^2}/(n_1 + n_2), \quad (6)$$

where n_1 and n_2 are the numbers of cutters which interact with coal and solid inclusions ($n_1 + n_2 = n_{c.c}$), respectively; ir_1 and ir_2 are the loading inequality ratios of a single cutter in cutting coal ($ir_1 = 3–4$) and stronger inclusions ($ir_1 = 5–14$). Higher values are assumed for ir_1 and ir_2 in complex structure coal seams.

Other than that, IR can be evaluated from a simplified expression below

$$IR = 1 + \left[3\sqrt{9 + n_{c.c}}/n_{c.c}\right]. \quad (7)$$

Under gradual stalling, the maximal force on the cutting head is

$$F_{CH\max} = IR\bar{F}_{CH}.$$

For cutter–loaders with two cutting heads, the maximal loads are determined for the common drive transmission and for transmission of each cutting head. The long-term strengths of the transmissions are calculated with respect to the value of the highest load.

The maximal torque of the common transmission in overloading of a cutting head is calculated as the sum of the maximal torque of this cutting head transmission and the average loads of the other cutting heads.

Limitation on the strength and durability of the transmission elements of coal-mining combines when excavating layers with strong inhomogeneities. Strength limit. As mentioned above, when the cutters of coal-mining combines interact with large solid inclusions, maximum loads occur that affect the strength of the transmission elements to the executive body. In this regard, the strength calculation of the transmission elements should be carried out according to the value of the maximum average peak load $\bar{Z}_{peak}$, determined when cutting a large solid inclusion with a chip thickness equal to the radial reach of the received cutter with one cutter. To ensure the required transmission life of 0.5 million tons and more than the extraction of the rock mass, it is necessary to consider the load that occurs simultaneously on two cutters [10].

When using engines of different power on the same combine, there may be a limitation of the operating mode in terms of the maximum torque for which the strength of the most loaded transmission element (usually gears) is calculated.

In general, this restriction can be represented as

$$M_{\max} = M_{avg} + M_{dyn} \le M_{pt}, \quad (8)$$

where M_{pt} is a permissible strength torque in the transmission to the executive body, N · m; $M_{\max}$, M_{avg} are the effective and average dynamic moments in the transmission to the executive body, respectively, N · m; M_{dyn} is the dynamic moment in the transmission, brought to the engine shaft, N · m.

For cases of meeting and cutting with one cutter of the executive body of a large solid inclusion in the process of steady-state operation, the permissible average torque $M_{avg.pt}$ brought to the drive shaft, is

$$M_{avg.pt} \le (M_{pt}/i_{gr}) - M_{dyn},$$

where i_{gr} is the gear ratio from the engine shaft to the shaft of the executive body.

The dynamic moment M_{dyn} is determined by the moment of resistance on the executive body when cutting through a large solid inclusion

$$M_{dyn} = Z_{peak.\max} D/(2i_{gr}) = \bar{Z}_{peak}(1 + 3\nu_{\bar{Z}_{peak}}) D/(2i_{gr}), \quad (9)$$

where $Z_{peak.\max}$ is the maximum value of the peak cutting force on the executive body when cutting through strong inhomogeneities, N, determined by the formula (5); D is the diameter of the executive body, m; $\bar{Z}_{peak}$ is the value of the average peak cutting force on the cutter, N, determined by the formula (1); $\nu_{\bar{Z}_{peac}}$ is the coefficient of variation of the average value of the average peak cutting force, determined by the formula (4).

In turn, the current moment in the transmission is

$$M_{\max} = D/2\left[F_c + \bar{Z}_{peak}\left(1 + 3\nu_{\bar{Z}_{peak}}\right)\right], \quad (10)$$

where F_c is the total cutting force on the executive body.

Using the expressions (8, 10), the permissible average value of the circumferential force on the actuator, reduced to the drive shaft Fcp.max, and the permissible strength of the transmission elements can be represented as

$$F_{cp.\max} \le \frac{2M_{pt}}{D} - \bar{Z}_{peak}\left(1 + 3\nu_{\bar{Z}_{peak}}\right).$$

Based on $F_{cp.\max}$, we can determine the permissible value of the feed rate.

The occurrence of the maximum moment is also possible with a monotonous overturning of the engine when several incisors of the executive body meet with a strong obstacle (small hard inclusions pulled out, rock substitutions). In this case,

$$M_{\max} \cong 1.5IR\frac{D}{2}F;$$

$$M_{avg.pt} \le \frac{M_{pt}}{i_{gr}\left[1 + k_g(IR - 1)\right]}. \quad (11)$$

The gain factor kg in the absence of special damping devices is assumed to be $k_g = 1$.

The calculation of the maximum loads in the transmissions to the individual executive bodies is made according to both options. The strength is calculated by the magnitude of the greatest load.

When creating new dredging machines, the design calculations solve the inverse problem of determining the maximum loads in the transmission to a separate executive body and in the general transmission when cutting through a large solid inclusion with a single cutter

$$M_{\max j} = M_{avgj} + M_{dynj}. \qquad (12)$$

The average moments of the M_{avgj} in the transmissions of individual executive bodies are taken as part of the average drive moment of Mavg.dr and are proportional to the calculated values of the cutting capacities. Its values are recommended to be taken according to Table 3.

The dynamic moment of M_{dynj} is determined by the formula (9), and the traction moment of the engine M_t – by the formula

$$M_t = M_{\max.fact}/(1 + 3\nu_{en}),$$

where $M_{\max.fact}$ is the maximum actual torque of the motor, taken depending on the characteristics of the transformer and the resistance of the mine electrical network that feeds the motor. The coefficient of variation of the engine load is equal to

$$\nu_{en} = \sqrt{K_{en_1}^2 \nu_{h.f}^2 + K_{en_2}^2 \nu_{l.f}^2},$$

where $\nu_{h.f}$ and $\nu_{1.f}$ are the total coefficients of variation of cutting forces for coal-mining combines with several executive bodies at high and low frequencies, respectively, determined by the formulas

$$\nu_{h.f} = \sqrt{\sum \left(\nu_{2i}^2 + \nu_{3i}^2\right)\left(\bar{M}_i / \bar{M}_{tr}\right)^2};$$

$$\nu_{l.f} = \sqrt{\sum (\nu_{1i}^2 + \nu_{5i}^2)(\bar{M}_i / \bar{M}_{tr})^2},$$

where $\bar{M}_i$ is the average torque for the engine of the i^{th} executive body, N · m; $\bar{M}_{tr}$ is the torque in the general drive of the combine, N · m.

The formulas included in the latter formulas ν_{1i}, ν_{5i} (low-frequency components of the coefficient of variation of loads), as well as K_{en_1} and K_{en_2}, are accepted according to the data given in the monograph by Posin E. Z. in co-authorship with Melamed V. Z. and Ton V. V. "Destruction of coal by mining machines". Formulas for calculating ν_{2i}, ν_{3i} (high-frequency components of the coefficient of variation) will be given below.

In the case of a monotonous rollover of the engine, when

$$M_{\max j} = k_{ov} M_{avgj},$$

where the values of the overload coefficient kov are calculated by the expression

$$k_{ov} = 1 + k_g(IR - 1).$$

For further calculations of the strength of the transmission elements, a higher value of the maximum torque is taken from the formulas (11, 12).

The maximum torque in the overall transmission of the combine when one of the executive bodies is overloaded is determined as the sum of the maximum torque in the transmission of this executive body $M_{\max j}$ and average loads on other executive bodies

$$M_{\max} = M_{\max j} + \sum_{j=1}^{j=n-1} M_{avg\,j}, \qquad (13)$$

where n is the ordinal number of the executive body.

Table 3

Recommended values of the average drive torque $M_{avg.dr}$

Drive type	Manual	Automatic control
One-engine	M_s (electromagnetic torque that ensures stable operation of the combine engine, N · m)	$0.9M_t$
Twin-engine kinematically coupled	$1.9M_s$	$1.7M_t$

When determining the static strength of the overall transmission, the higher of the calculated values $M_{\max}$ according to the formula is taken (13).

Durability limit. To calculate the fatigue strength of the transmission elements of dredging machines, the load spectrum is determined, which characterizes the spread of forces relative to the average. At the same time, to determine the limits on the durability of the transmission elements, the initial data is used:

- the permissible amplitude of the equivalent torque $M_{eq.perm}$ (N · m) at a continuous load spectrum, taken to calculate the teeth of the wheels for bending and contact endurance and the shafts for bending endurance: $M_{eq.perm} \geq k_1 M_{\max}$;

- the permissible amplitude of the equivalent torque $M'_{eq.perm}$ (N · m) used to calculate the torsional fatigue strength of the shafts: $M'_{eq.perm} \geq k'_l M_{A\max}$.

In these expressions: k_1 and k'_l are durability coefficients, taken depending on the type of loading of the transmission elements; $M_{\max}$ is the maximum long-acting torque applied to the engine shaft, (N · m); $M_{A\max}$ is the maximum long-acting torque amplitude applied to the engine shaft (N · m).

Taking into account the fact that the load for calculating the fatigue strength of the transmission elements is determined by the level of the average load and the load spectrum (the spread around the average load), we have

$$M_{\max} = (1 + 3n_{tr})M_{avg};$$

$$M_{A\max} = 3v_{tr}M_{avg},$$

where v_{tr} is the coefficient of variation of the load in the transmission to the executive body, determined by the formula

$$\nu_{tr} = \sqrt{\nu_{1i}^2 + k_g(\nu_{2i}^2 + \nu_{3i}^2) + \nu_{4i}^2 + \nu_{5i}^2}. \qquad (14)$$

A dependence is proposed for determining the value of the permissible average torque ($M_{tr.\max}$), which, with varying load variations in the transmission, with a margin factor equal to 1, will correspond to the equivalent moment taken in the strength calculation

$$M_{tr.\max} = \frac{M_{eq} k_{st}^2 (1 - \nu_{tr}^{2,4})^3}{m_{eq}} \sqrt[3]{\frac{T_b}{T_r}},$$

where M_{eq}, k_{st} are respectively, the calculated equivalent torque and the reserve coefficient of the most loaded transmission wheel; m_{eq} is the equivalence coefficient; T_b and T_r are respectively, the basic and required design durability.

From (14) it follows that in the modern interpretation, the spectrum of loads on the executive body is considered as the sum of independent low-frequency (v_{1i}, v_{4i}, v_{5i}) and high-frequency components (v_{2i}, v_{3i}), caused by:

a) the influence of design factors that lead to a periodic change in the number of cutters simultaneously involved in cutting, and a change in the average cutting force on the executive body as a result;

b) features of the brittle fracture of coal, which is characterized by an uneven (sawtooth) view of the diagram of changes in forces on a single tool. Taking into account the actual arrangement of the cutters, the values of the coefficient of variation of the load on the executive body of the coal-mining combine are determined by the formula

$$v_{2_i} = v_z \sqrt{\sum_{i=1}^{n_{cut}} \left(Z_i / F_{\min}\right)^2},$$

where Z_i is the cutting force on each of the i^{th} cutters involved in cutting, N; $F_{\min}$ is the minimum load on the executive body;

ncut is the number of cutters simultaneously involved in cutting the coal mass.

The coefficient of variation of the cutting force on the cutter v_z, depending on the features of the structure of the formation, is taken in the range of 0.5–1.2;

c) the variability of the resistance of the formation to cutting Al in the section processed by the executive body, which, together with the influence of the arrangement of the cutters, causes a variation in the load

$$v_{3_i} = v_{AC}\sqrt{\sum_{i=1}^{n_{cut}}\left(Z_i / F_{\min}\right)^2}.$$

The coefficient v_{AC}, which characterizes the variability of the formation resistance to cutting A_l in the cross section of the coal face, varies from 0.47 at A_l 120 N/mm to 0.3 at A_l 300 N/mm;

d) the variability of the resistance of the formation to cutting A_l along the length of the lava, causing low-frequency changes in the load. The values of the coefficient v_{4i} vary from 0.25 at A_l 20 N/mm to 0.12 at A_l 120 N/mm;

e) the variability of the load caused by the uneven movement of the coal-mining combine. The coefficient of variation v_{5i} (the limit of variation 0.35–0.05) increases with an increase in the average load, decreases with an increase in the feed rate and linearly depends on the rigidity of the feed system.

Stability of coal mining combines. In cases where the loads on the executive bodies when cutting large solid inclusions and strong rock layers contained in the coal seam, exceed the maximum permissible level, the stability of the combines is violated. In this regard, the stability calculation should be carried out according to the maximum possible values of external loads that occur during the destruction of layers of a complex structure.

External forces acting on the cleaning combine are conventionally divided into disturbing and restoring ones. The perturbations depend on the loads on the executive body, which include the resultant cutting force and the part of the feed force required to carry out the process of destruction of the coal face. Restoring forces include gravity, coal loading resistance, tension of the idle branch of the traction chain, part of the feed force, etc.

In general, the stability of the combine during operation is observed if the moment of the disturbing forces M_d relative to the possible axis of rotation does not exceed the moment of the restoring forces M_r relative to the same axis, i.e. if the condition is met

$$M_d \le M_r.$$

The stability of the combine harvesters is mainly affected by low-frequency changes in the disturbing forces. In this connection, the total coefficient of variation of the perturbing moment required for calculating stability is determined by the formula

$$\nu_d = \sqrt{\nu_{1i}^2 + \nu_{4i}^2 + \nu_{5i}^2}.$$

The moment of the disturbing forces (N · m) is equal to

$$M_d = \bar{M}_d(1 + K v_c),$$

where $\bar{M}_d$ is the average value of the disturbing moment, N · m; K is the standard deviation.

The permissible value of the average torque M_{crit} (N · m) is determined by the expression

$$M_{crit} = \bar{M}_{d.\lim}(1 + K\nu_c),$$

where $\bar{M}_{d.\lim}$ is the limiting moment of disturbing forces, N · m.

This expression can be used as a constraint when determining the permissible value of the average torque and selecting the operating parameters.

When performing calculations based on the approximate limit moment $M_{\lim}$, determined without taking into account the variability of loads, the static stability of combines operating from the conveyor frame is provided if the condition is met

$$M_{\lim} > \left(1 + \sqrt{2\nu_k}\right) M_{tt}, \qquad (15)$$

where M_{tt} is the engine traction torque, N · m.

The coefficient of variation v_k for auger actuators operating on reservoirs with a capacity of more than 1.3 m is assumed to be 0.5, and when working on reservoirs with a layer power greater than 1.3 m and $v_d = 0.25$.

The calculation of the limiting moment of the $M_{\lim}$ for stability and the reference reactions are determined by drawing up and solving a system of equations describing the equilibrium position of the combine during turns relative to the sides of the reference polygon, taking into account different operating modes. In this case, along with the forces acting on the executive body, the forces of the weight G of the combine, the loading resistance F_{res}, the tension of the idle branch of the traction body R_x, the feed force Y_f, the resultant cutting forces on the executive body [11], the components of the reference reactions and the coordinates of the points of application of all forces [12, 13] are taken into account.

The stability of the combine is determined for the course down and up the lava at the maximum and minimum extracted reservoir capacity, the minimum and maximum angles of incidence for which the use of this type of combine is designed. The operating modes are set by the torque on the motor shaft (from zero to the maximum bench).

If, as a result of the calculations performed, the condition (15) is not satisfied, then a decision is made to make structural changes to the combine to ensure its stability (at $M_{\lim} < 1.1M_{tt}$) or a refined stability calculation is made at $1.1M_{tt} < M_{\lim} \le \le \left(1 + \sqrt{2\nu_{\mathrm{k}}}\right) M_{tt}$, for cases of normal operation before a monotonous rollover and a meeting of the executive body with a large solid inclusion (a strong rock layer).

The stability of the harvester during its normal operation is considered acceptable if the limiting torque $M_{\max.st} \ge 1.1M_{tt}$.

The limiting torque for the least stable operation scheme is equal to

$$M_{\max.st} = \bar{M}_{gen} M_r \Delta_{2\lim} / \bar{M}_d,$$

where $\bar{M}_{gen}$ is the average torque in the overall drive of the combine; $\Delta_{2\lim}$ is the limit value of the coefficient of influence of the variability of the disturbing moment, determined when solving a system of equations describing the equilibrium position of the combine. Usually, $\Delta_{2\lim} < 1$.

When checking the stability of the combine for the case of meeting with a solid obstacle, the location of a large solid inclusion, which creates the greatest disturbing moment when it is cut, is evaluated. The stability calculation consists in determining the height of the H_{sup} lift of the support that stabilizes the harvester in the formation plane, and comparing it with the height of the side cheek of the H_{ski} support ski. The stability of the combine is considered secured if $H_{sup} < 0.7H_{ski}$.

To reduce the disturbing moments, it is recommended:

- to place the executive bodies as close as possible to the center of the combine body;
- to apply counter rotation of the executive bodies;
- if possible, to position the incisors on the executive bodies evenly;
- to provide for such a support structure that the resultant of all external forces at any combination of them passes through the support surfaces.

In order to obtain the initial data for calculating the stability of the cutting machine, the resultant cutting forces and the coordinates of the points of their application for various positions of the executive bodies are determined.

Conclusions. Finally, the research findings allow coming to the conclusions that:

1. The highest loads on a cutter arise in central cutting of a solid inclusion; for this reason, the strength and durability of a cutter should be calculated for this mode of the cutter–inclusion interaction.

2. The maximal loads in cutting with a single cutter and with a group of cutters on a cutting head of a cutter–loader should be calculated with regard to the cutting mode (depth and width of cut) and geometry of the cutting edge of cutters.

3. The maximal instantaneous torque on transmission of cutting heads should be calculated with regard to the maximal possible average peak cutting force in cutting solid inclusions and hard dirt bands.

4. A significant variation in the loads on the executive body (for combines of different types (v_{tr} = 0.3–0.6) is one of the main reasons for reducing the reliability of coal mining machines and their components.

5. When cutting large-sized strong inhomogeneities contained in coal seams of complex structure, loads are formed on the executive bodies that exceed the maximum permissible level, which violates the stability of combines.

6. When designing combines engineered for excavating layers of complex structure, the choice of electric motors should be carried out according to the maximum possible values of external loads that occur when encountering strong inhomogeneities, taking into account possible failures of tool holders in such conditions.

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Закономірності формування максимальних навантажень на різцях і виконавчих органах вугледобувних машин

Ю. М. Лінник[1], *В. Ю. Лінник*[1], *С. А. Прокопенко*[2], *А. Цих*[3]

1 – Федеральний державний бюджетний освітній заклад вищої освіти «Державний університет управління», м. Москва, Російська Федерація, e-mail: vy_linnik@guu.ru

2 – Федеральний державний автономний освітній заклад вищої освіти «Національний дослідницький Томський політехнічний університет», м Кемерово, Російська Федерація

3 – Фрайбурзька Академія, м. Одервіц, Федеративна Республіка Німеччина

Мета. Встановити вплив режиму різання й геометрії різців на динамічні навантаження за різних сценаріїв взаємодії різця із твердим включенням.

Методика. Математичне моделювання, статистичний аналіз.

Результати. Руйнування вугільних пластів складної будови, що містять міцні неоднорідності (тверді включення й міцні породні прошарки), супроводжується дією на різці виконавчих органів вугледобувних машин динамічних навантажень, які викликають зниження продуктивності процесу виїмки вугілля й передчасний вихід з ладу їх вузлів і елементів. Це знижує ефективність різання та призводить до передчасного виходу з ладу вузлів і деталей. Встановлено, що при прорізанні різцем включення та при торканні з ним розміри останнього практично не впливають на величину пікового навантаження. Навпаки, для випадків вириву, величина пікової сили різання істотно залежить від розмірів і конфігурації включення, а також крихко-пластичних властивостей вугілля, що визначають характер зв'язку включення з масивом. Установлено, що з усіх видів взаємодії різця із твердим включенням найбільші навантаження виникають при їх центральному перерізанні. Також розглянуто механізм і характер виникнення навантажень при короткочасному перерізанні групою різців великих (нероздроблених) твердих включень. Установлено, що максимальні навантаження на групах різців виконавчого органу можуть також виникати при монотонному перекиданні електродвигуна комбайна, коли середній рівень навантаження наближається до тягового моменту двигуна, через зустрічі декількох різців з великими твердими включеннями, при підрубуванні порід покрівлі й перерізанні міцних породних прошарків.

Наукова новизна. Установлені ймовірності перерізання різцем твердого включення за різних рівнів напрацювання виконавчого органу та час дії максимального пікового навантаження при виїмці смуги вугілля довжиною 100 м. Запропоновані розрахункові залежності для визначення рівня й часу дії максимального навантаження на групі різців при прорізанні міцних неоднорідностей, коефіцієнтів її варіації та нерівномірності навантаженості виконавчого органу.

Практична значимість. Отримані результати необхідно приймати за основу при визначенні максимального динамічного моменту у трансмісії до виконавчого органу, за величиною якого ведеться розрахунок на міцність елементів трансмісії.

Ключові слова: *вугілля, різець, виконавчий орган, вугледобувна машина, тверді включення, сила різання, опірність різанню*

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