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Technical Note

A New Approach to the Design of Drilling Tools

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1 Introduction

An effectiveness of mining largely depends on the driling rate, which is determined in great part by a drilling bit shape and properties.So, the optimal design of drilling tool is currently a very important problem. The following two ways to improve drilling are commonly used: first,experimental, and second, basing on the simulation of stress state and rock fragmentation in drilling. Possibilities of these ways are limited : the problem of 3-D simulation of deformation and fragmentation of heterogeneous rock under loading with intricately shaped tool is rather complex and has not been solved yet.

The paper seeks to develop a principle and method of design and improvement of drilling tool , which could make it possible to create new high-efficient drilling bit constructions.

Currently, the methods of information theory are widely used to describe a behaviour of complex systems [1]. In particular, the deformation and failure of granular, heterogeneous or damaged materials can be described with the use of these methods (see, for example,[2,3]).Besides, the ill-posed problems or problems which use inaccurate data are solved by the methods as well [4,5].

The drilling bit are commonly intricately-shaped, consist on a number of elements, and their shape is changed in drilling due to wear.To work out methods to improve the tool, one need develop a parameter characterizing which does not depend on the symmetry of tool and allows any complexity of tool shape.Here it is suggested to use for that an informational entropy of distribution of contact stress. The relation between this value and arbitrary contact stress distribution function is deduced. Then, we use the methods of the information theory and the continuum damage mechanics to relate the parameter of tool shape and the intensity of rock destruction in drilling. The conclusion about a relation between the informational characteristics of tool shape and the intensity of rock destruction is generalized and a principle of drilling tool improvement is formulated. Results which are obtained with the use of the model are compared with the results of analysis of patents and technical solutions.

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2 Informational entropy of contact stress distribution as a characteristic of drilling tool shape

It is known that the rock failure in indentation depends on the indentor shape. Consider three simplest form of indentors: spherical,conical and cylindrical ones. Zhlobinsky [6,7] has made experiments on the indentation of differently shaped indentors into limestone, and has discovered that the volume of craters of spalled rock was maximal for conical, minimal for spherical and medium for cylindrical indentors (the ratio was about 2.1:1:1.56). If one compares the result with the contact stress distributions for these cases which have been obtained theoretically by Galin [8], one can see that the maximal volume of crater corresponds to the maximum sharp curve of contact stress distribution, whereas the minimal volume corresponds to the most homogeneous contact stress distribution. One can suppose that the "sharpness" (i.e. non-homogeneity) of contact stress distribution is a parameter which determines the intensity of rock fracture (in this case, the volume of spalled rock).

To characterize this "sharpness" numerically for arbitrary tool shape (including,for example, non-axisymmetric bit with many teeth), one can use an informational entropy of contact stress distribution [9]. Suppose that a contact stress distribution function is given as follows

$$\sigma_c = F(x, y, z) \tag{1}$$

where x,y,z - coordinates of a contact point.It is clear that the function is determined by the tool shape and the stress-strain relationship for given rock.Peaks of the function correspond to stress concentrators on the drill bit surface.

From eq.(1) one can obtain the probability distribution of contact stress over the contact surface:

$$p(\sigma_c) = (1/N) \sum_i Y[F(x, y, z); \sigma(c)] \tag{2}$$

where N - the amount of quantizing levels of σ_c, i - the contact point number, Y[] - step function,$Y[\alpha; \beta] = 1$, when $\alpha = \beta$ and is equal to 0, otherwise.

The informational entropy of contact stress distribution can be calculated by the formula [9,10,11]]:

$$H_c = -\int_{\sigma_c} p(\sigma_c) \ln p(\sigma_c) d\sigma_c \tag{3}$$

This value characterizes the "sharpness" (non-homogeneity) of contact stress distribution for arbitrary function F, and,thus, for arbitrary drilling bit shape.The greater the parameter H, the more unhomogeneous the contact stress distribution.

3 Influence of tool shape on the damage accumulation

Comparing the experimental data on the crater volume in indentation [6] with the contact stress distributions for the indentors [8], one can suppose that the parameter H_c (which characterizes the "sharpness" of the contact stress distribution) and the intensity of rock fragmentation (which can be characterized by crater volume) are related.

To characterize the intensity of rock fragmentation in the theoretical model, one can use the damage parameter of the strained volume [12].It is clear that the greater is the damage parameter (i.e. the average density of microcracks throughout strained rock volume) the greater is the volume of failed and removed rock [9].

Consider the relation between H_c and the damage. Suppose that the volume V of rock is loaded by an intricately-shaped drilling tool.The initial damage of rock will occur at the contact surface, in the vicinity of stress concentrators.Let the damage (microcrack) be formed in the given point of contact surface provided the local stress exceeds some critical level.Then, one can calculate the initial damage by formula [9,15]:

$$Do = \int_{\sigma} R(\sigma_c) d\sigma_c \tag{4}$$

where Do is the initial density of microcracks (damage) on the contact surface,$R(\sigma_c)$ is a probability of a microcrack formation in a given point at stress $|sigma_c$. The function $R(\sigma_c)$ is given in [9,15] and looks as follows:

$$R(\sigma_c) = \exp(-k\sigma_{cr}^2/\sigma_c^2) \tag{5}$$

where σ_{cr} is the local strength of rock, $k = (1+\mu)/3E$, μ - the Poisson's ration, E - the Young modulus.

As a first approximation one can suppose that the function $p(\sigma_c)$ is given by exponential function (more general cases will be considered below). For this case there is a linear relation between the entropy and the mean value [1,10].

Substituting the formula of exponential distribution into (4) and taking ino account the relation between the entropy and expectation, one can obtain the following relation between the initial damage Do in the rock and the informational characteristics of drilling bit shape

$$Do \propto exp(\lambda H_c) \tag{6}$$

where λ- some constant.

In the initial stage of the tool/rock interaction the value Do is the density of as-formed microracks.

Then,consider the damage growth in rock. As was shown by Lemaitre [12], the damage evolution is described as follows:

$$dD/dt = C_0\sigma^2/E(1-D)^2 \tag{7}$$

where D - the damage parameter, E - the Young modulus of the material, σ - stress,C_0 - a coefficient which includes the triaxility function, the damage threshold function , strain rate and material constants [12].

From eq.(7) one can obtain after some manipulations (if one suppose that the initial damage is equal to surface damage Do)

$$D = 1 - [(1 - Do)^3 - 3W]^{1/3} \tag{8}$$

where $W = (1/E) \int_t C_0 \sigma^2 dt$ is a function of loading conditions.

Eqs.(6), (8) relate the shape of drilling tool which is characterized by the informational entropy of contact stress distribution and the damage parameter of rock.

From eqs.(6), (8) it follows that the more the unevenness of the contact stress distribution over the contact surface, the greater the microcracks density in the rock (at the same load).That means that the greater the informational entropy of contact stresses distribution, the greater the destructing ability of drilling tool.

Thus, the parameter H_c can be considered as a general characteristic of drilling tool shape.

4 Computation and results

To test the above conclusion about the relation between the entropy of contact stress distribution and the destructing ability of tool, the entropy and initial damage for a series of contact stress distributions were calculated. The destructing ability of tool is characterized by the damage which are formed as a result of loading rock by given load but with different tool shapes.

To obtain the damage versus the contact stress entropy relation for a number of contact stress distributions, the function (1) was approximated by power function:

$$\sigma_c(x) = q(x/a)^n \tag{9}$$

where $2a$ is the width of contact area, n -a power coefficient which determines the appearance of contact stress distribution, q - a coefficient which is calculated from the condition of constant load, x - a distance between a point and the axis of tool. Integrating eq.(9), we obtain

$$q = (n+1)P/(a^{n+1}) \tag{10}$$

where P is the load.

The case when $n > 1$ corresponds to extremely sharp tool; when $0<n<1$ it correspons to more real case when the tool has a convex surface.

The values of initial damage Do and the contact stress entropy were calculated by formulas (3), (4) and (2) for such conditions. The coefficient n has been changed from 0.2 to 2.5.The number of levels N was 1000, the contact surface was discretized also for 1000 elements. The width of contact surface was 10. The step of discretization of contact stress was 0.1. The load P is equal to 25. The local strength of rock (i.e. the contact stress at which a microcrack forms) is equal to 21. The wear of tool was not taken into account.

A plot of surface damage Do versus the contact stress entropy is presented at Fig.1.

From Fig.1 one can see that the surface damage increases with increasing contact stress entropy (at constant load).Taking into account the relation between the surface (initial) damage and the total damage (eq.(8)), one can make a conclusion, that the destructing ability of tool is the more, the grater is the informational entropy of contact stress distribution.

5 Principle of drilling bit design and analysis of technical solutions and patents

It is of interest to compare the obtained conclusion about the relation between the damage in rock and the contact stress entropy of drilling tool with some other data relative to the influence of statistical heterogeneity of tool properties on the drilling process. In [17] the influence of teeth orientation on the drilling efficiency was considered, and it has been shown that the dissimilar orientation of different teeth on the same auger allows to increase the rate of drilling. Moscalev et al.[16] have proved that non-uniform (in grours or in pairs, for example) placing of teeth over the drill bit makes it possible to increase the drilling rate relatively to the drilling rate at the uniform placing of teeth. In [18], it has been shown that different profiles of parts of a diamond bit can ensure an increase in the drilling rate as well.

On the other hand, it is known that the combination of hard diamonds and soft bond in grinding wheels ensures the self-sharpening of the wheels [19,20]. One can suppose that the heterogeneity of wear-resistances in differeent points of contact surface can ensure self-sharpening of other types of tool as well [14].

If one tries to compare the obtained conclusion with these data, and to generalize them, one can state the following principle of drilling tool design: the efficiency of the drilling tool increases with increasing the heterogeneity of distribution of local parameters of tool. We have considered above the distribution of contact stress; in cited works, these local parameters are the orientation of teeth on the auger [17], the distance between the teeth on drill bit [16],the shape of diamond bit profile [18], the local strength (wear-resistance) of points of contact surface [19,20] .

The heterogeneity of any distribution can be characterized by the informational entropy [10,11]. Thus, one can formulate the principle as follows: the greater are the informational entropies of distributed parameters of drilling tool the more is the tool efficiency.

To test the formulated principle and the possibility of its practical application, technical solutions and patents in the area of drilling tool improvement were analyzed. It was considered about 250 patents.

As a result the patents were divided into following seven groups according to the used ways to improve a tool: introduction of unevenness into the tool work surface; asymmetry of tool work surface about speed vector; using teeth of dissimilar shapes and/or orientations on the same auger; unevenness of teeth arrangement on the auger; using the destructing elements with different loading mechanisms (for example, combining cutting and impact elements); different wear-resistances of different points of tool working surface; self-sharpening and self-organization of tool.

The results of the analysis as well as the examples of the patents are given in Table 1.

Comparing the results given in the Table 1 with the stated principle, one can conclude that the results of patents analysis substantiate this principle: all directions of tool improvement which are presented in the Table 1 can be considered as particular cases of application of this principle. In all cases the tool is improved at the expense of increase in unevenness of distribution of its local parameters (teeth orientations, distances between teeth,mechanisms of loading,wear-resistances,etc).

Thus, on the basis of the theoretical model and the analysis of the technocal solutions,we

Table 1: Technical solutions in the area of tool design

Main ideas	Some examples
1. Unevenness of the tool work surface: making a cutting face convex or concave, or prismatic or cylindrical lugs on cutting face; stepped working surface; cavities, bevels, slopes on the tool working surface	No 1044765A, 1023062A, No. 1323706A1, 623958 (USSR); No. 1284539 (UK) No 57- 35357 (Japan)
2. Asymmetry of tool working surface about direction of tool movement: a cutting face or its parts are inclined to the cutting vector	723123 and 1046465A (USSR)
3. Using teeth of dissimilar shapes or orientations on the same bit: combination of radial and tangential cutters; different cutting and wedge angles on teeth from one bit; using different materials of inserts; the strength of inserts changes from axis of auger to periphery.	No. 395559, 153680A1, 1366627A1 (USSR)
4. Irregular arrangement of teeth on a bit: teeth or cutters are placed in pairs or in groups; various distance between teeth	No. 3726350, 3158216 (USA) No. 1472623A1 (USSR)
5. Elements with different mechanisms of loading on a bit are combined: combination of mobile and fixed elements,or rotating and progressively moving elements, or cutting and impact elements	No. 52-48082 (Japan) 697711 (USSR)
6. Different wear-resistances of different points of tool working surface: layers with different strengths in a cutter; diamond coatings and graded materials; cavities of required shape in tool	No. 714003, 281349. 145496, 693000, 609884 (USSR)
7. Self-sharpening and self-organisation of tool	No.4230193 (USA) No.717327, 719192 (USSR)

can conclude that the general way to improve the drilling tool is to increase the informational entropies of distribution of local parameters of tool.

6 Conclusions

The general principle of improvement of drilling bit is formulated as follows: to improve the drilling tool and increase its efficiency, one should raise the informational entropies of distributions of local parameters of the tool.Among the parameters are the contact stress, wear-resistance in a point of tool work surface, orientation of teeth and distances between them on the bit, mechanism of rock loading by a tooth, rate and direction of loading by an element of bit etc.

The validity of the principle is substantiated by the analysis of main ideas of technical solutions and patents.

7 References

1.Wilson A.G., *Entropy in Urban and Regional Modelling*, Pion Ltd, London, 1970

2.Brown C.B., Entropy Methods in the Consitutive Modelling of Granular Flow, Proc.2nd Int.Conf."Powder and Grains-93", Balkema, Rotterdam,1993

3.Ostoja-Starzewski M., Damage in a Random Microstructure: Size Effects, Fractals and Entropy Maximization, in: Mechanics Pan-America-1989 (ed.C.R.Steele et al.), ASME Press, NY, 1989, pp.202-213

4.Tarantola A. and Valette B., Inverse Probleme = Quest for Information, J.Geophys, 1982, 50:159-170

5.Rietsch E., The Maximum Entropy Approach to the Inverse Problems, J.Geophys, 1977, 42, pp.489-506

6.Zhlobinsky B.A., *Impact Fracture of Rocks under Indentation*, Nedra, Moscow, 1970 (in Russian)

7.Mishnaevsky Jr L.L. A Brief Review of soviet Theoretical Approaches to Dynamic Rock Failure, Int.J. Rock Mech. Min.Sci., Vol.30, No.6, 1993

8.Galin,L.A. , *Contact Problems in the Theory of Elasticity*, Ed.I.N. Sneddon, North Carolina State College, 1961 (Translated from the Russian).

9.Mishnaevsky,Jr, L.L. Informational Model of Rock Destruction and the Principle of Mining Tool Improvement, in: Fracture and Damage of Concrete and Rock (FDCR-2) (ed. H.P.Rossmanith),E FSpon, London, 1993

10.Longo,G. *Selected Topics in Information Theory* (CISM Course, Udine, No.18), Springer Verlag, Wien, NY, 1973

11.Stratonovich R.L., *Theory of Information*, Sovetskoye Radio, Moscow 1975 (in Russian)

12.Lemaitre,J, *A Course on Damage Mechanics*, Springer Verlag, Berlin, 1992

13.Chugh C.P.,*High Technology in Drilling and Exploration*, Balkema, Rotterdam, 1992

14.Mishnaevsky Jr,L.L. Mathematical Modelling of Wear of Cemented Carbide Tools in Cutting Brittle Materials, Int.J. Machine Tools and Manufacture, Vol.35 No.5, 1995, pp.717-724.

15.Mishnaevsky Jr L.L. Probabilistic Model of Failure of Composites under Dynamical Loading. Presented at ESIS Symposium on Impact and Dynamic Failure of Polymers and Composites, Sardinia, Italy, 20 - 23 Sept.1993

16.Moskalev A.N. et al, *Increase in Intensity of Rock Fragmentation Processes*, Moscow, Nauka, 1978 (in Russian)

17.Fedorov V.S.*Research Foundations of Drilling Regimes*, Moscow, Gostoptekxizdat, 1951 (in Russian)

18.Artsimovich G.V.*Mechanical and Physical Foundations of Design of Rock-Breaking Drilling Tool*, Novosibirsk, Nauka, 1985 (in Russian)

19.Mischnajewskij L.L., Verschleiss von Diamant und CBN- Scheiben beim Schleifen zaeher Metalle, Ind. Diamante Rundschau, 1993, No.1

20.Mishnaevsky, L.L. *The Wear of Grinding Wheels.* Naukova Dumka, Kiev, 1982 (in Russian)