A study on directions of significant efficiency increase of rock fracture by tools equipped with super hard inserts from composite

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Abstract. In the paper the directions of a significant increase in effectiveness of mine rocks destruction by tools equipped with super hard inserts from composite materials are reviewed and justified. Designs of mining drill bits with the cutting insert in the form of elliptical Cassinian oval and the asymmetric ring cleaves are suggested. Versions of laboratory stand constructions are developed in order to determine the power consumption of rock destruction.

1. Introduction

In mining industry major part of finances is used to arrange the works associated with crushing the rocks. During mechanical impact on rocks with special tools in order to crush it the tool itself also experiences high loads depending on physics-mechanical rock properties [1]. Two tasks become actual in this situation – provision of a significantly much higher tool strength compared to the strength of rocks, and creation of such tool forms that would make the crushing process less power consuming.

The most demanded rock crushing tool used at present at many coal and ore mines is a cutting bit of drilling machines and coal cutting machines: radial, tangential, rotating, blades for rotary drilling and also bladeless drilling crown bits [2]. Search for scientific and technical solutions to improve the efficiency of rock destruction with mining tool is an actual task for mining industry. The implementation of such studies in recent years is carried out by the Institute of Coal RAS SB within FCP theme: "Development of experimental combined tool designs using the super hard composite materials for the efficient rock destruction". The solution of the problem in the ongoing studies is expected to be achieved by means of theoretical justification of samples design of the combined instrument on the basis of reinforcing inserts from super hard composite materials with the further study of their interaction with the rock on specially designed laboratory benches.

2. Research into the problem

Efficiency increase of rock crushing by mining tool can be achieved by different means: changes in tool geometry, use of new more productive and energy efficient modes of rock crushing, as well as the use of new materials in the manufacture of cutting inserts [3]. The first direction includes research on the development of various types of mining tools structures, providing guaranteed turnability of revolving cutters, prevention of rear cutter face from lowering, more rational armoring of bladeless

tool, as well as expansion of application range of radial cutters according to the rocks strength without changing the cutting insert geometry.

Based on the results of the fulfilled researches new designs of drill bits are developed: with a cutting insert in the shape of Cassinian elliptical oval [4] and also with asymmetric ring cleave [5]. The cutter with a cutting insert of elliptical Cassinian oval shape is shown in Figure 1a. It consists of a body 1, two wings with hard alloy inserts 2 of elliptical Cassinian oval shape, blades of which 3 are set along the big oval axis, wherein the big axes of the ovals are inclined to the tool axis at an acute angle α (Figure 1a).

One of the properties of elliptical Cassinian oval is the presence of two points with a curvature tending to infinity, which allows the full contact to be achieved when interacting with the face at these points. This feature of the cutter helps to reduce cutter blades blunting 3, in contrast to the existing cutters, in which the interaction of the blades with the face is carried out along the stress concentrators placed on them.

In order to reduce the energy consumption of rock drilling, by providing their destruction with large cut-offs, within the frames of the study the drilling bit with asymmetric ring cleave was designed (Figure 1b). The drilling bit was created on the basis of RKS bit design, consisting of a body and discontinuous blades placed symmetrically to the bit axis [6]. The disadvantage of the RKS tool is the fact that both inner semi-blades cut on the face of the borehole concentric strips, easily imposed on each other, which does not lead to active face destruction between the cutting strips, i.e. power consumption of destruction process is high.
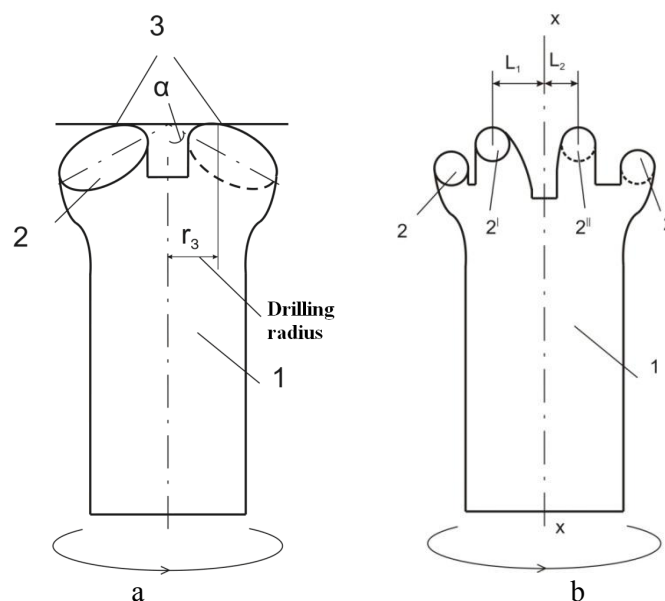

Figure 1. Drilling bits with the cutting insert of elliptical Cassinian oval shape (a) and asymmetric ring cleave (b).

Considering this drawback of PKS cutter, in the design of the cutter with asymmetric ring cleave the inner semi-blades are located asymmetrically with respect to the axis of the cutter rotation (Figure 1b). The developed cutter design with asymmetrical ring cleave allows on its basis the cutters with different semi-blade combinations to be created corresponding to any given borehole drilling conditions.

Drilling tool with asymmetrical ring cleave (Figure 1b) consists of a body 1, two wings with discontinuous blades designed as peripheral 2 and the internal 2' and 2" semi-blades, while internal semi-blades 2' and 2" are set asymmetrically with respect to cutter axis, at a distance L_1 and L_2. During drilling, the cutter is rotated according to the arrow in Figure 1b with simultaneous axial advance to

the face. Semi-blades 2, 2' and 2" start cutting rock from the face. Due to the asymmetric installation of internal semi-blades 2' and 2" the cut strips overlap with each other, thus, providing face destruction of the drilled borehole with big pieces, that results in reduction of power consumption of the drilling process.

As it was previously noted, when considering ways to improve the efficiency of rocks destruction by drilling cutters, one of the most urgent problems to be solved during their design process is to prevent the rock shear by the cutter rear side. Theoretical studies carried out in the framework of the Federal Target Program, allowed fundamentally new designs of cutting blades of drilling bits to be justified.

In Figure 2 the bit movement geometry can be seen, performing rotational movement around the axis $0'0$ with speed ω and simultaneous forward advance into the depth h per one revolution.
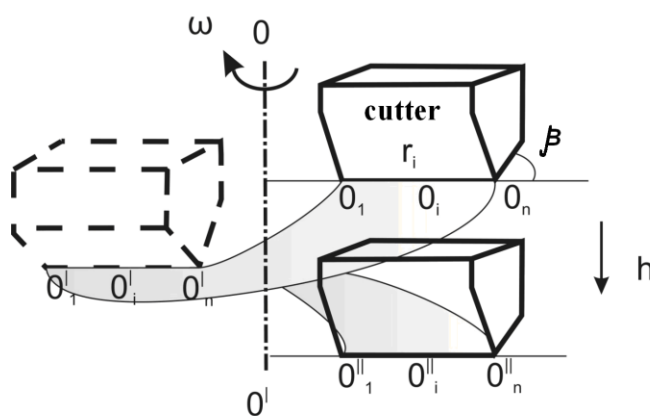

Figure 2. Geometry of drilling bit movement.

From Figure 2 it can be seen that each point of the cutter blade 0_1, 0_i, … 0_n, at distance r_i from the tool axis, passes the path $0_10'_10''_1$, $0_i0'_i0''_i$, … $0_n0'_n0''_n$ per one cutter turnover. Helical trajectory scan of each point 0_1, 0_i, … 0_n in Figure 2 represents the hypotenuse of a right triangle, the legs of which are the distances of the drilling tool advance h and the circumference length with r_i radius described with a corresponding point relative to the axis $0'0$ (Figure 3a). The trajectory of each cutter blade point is the angle of inclination α_i with the cutting plane of the cutter at a zero advance (Figure 3a). This angle can be found as:

$$\alpha_i = arctg\,\frac{h}{2\pi r_i}.$$

(1)

From relation (1) it can be seen that the value of the angle αi is a variable and decreases from the blade inner edge to its outer edge. This fact imposes certain restrictions on the clearance value of rear cutters angle β since achieving equality $\alpha i = \beta$ drilling cutter stops cutting, causing the rock shear.
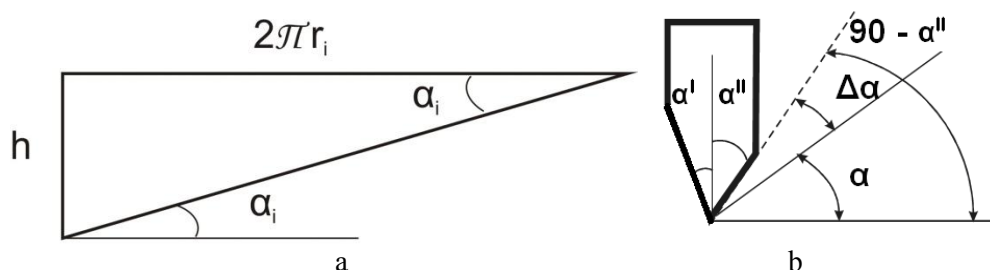

Figure 3. Helical trajectory scan of the cutter point (a) and cutting geometry (b).

Usually, in practice [6], the mining tools rear angle is within $5° \div 20°$. With positive front angle the rear angle increase leads to weakening of the cutting edge of the tool and may lead to its failure. With

negative front angle, as the studies have shown, rear angle can be increased up to 20°÷30°, as the strength of the cutting edge is not reduced, and the wear areas have smaller dimensions.

It is obvious that the the strength of the cutting edge depends directly on the angle of its sharpening which is composed of the front $\alpha^{|}$ and rear $\alpha^{||}$ sharpening angles (Figure 3b). At the same time, to guarantee the prevention from rock shear by the rear cutter blade, the difference Δα between the cutting angle α and the rear sharpening angle should be provided in accordance with condition (2).

$$\Delta\alpha = (90 - \alpha^{||}) - \alpha .$$
(2)

The cutter design corresponding to condition (2) can be obtained when using variable values of back sharpening angle $\alpha^{||}$ over the entire length of the blade [7]. Considering the plots in Figure 3a and using drilling cutter advance value h, we can calculate the sharpening angle value $\alpha^{||}$ for any point of the blade (Figure 4).
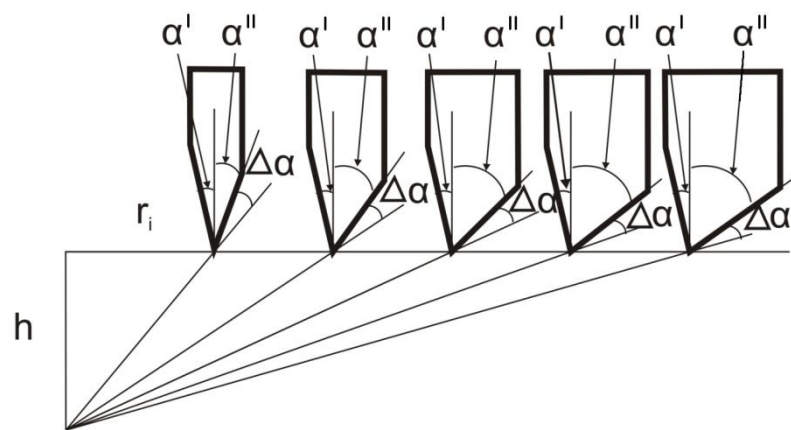

Figure 4. Variation of the rear angle of cutter sharpening from the cleave to periphery.

Thus, the implementation of a variable adjustable sharpening angle $\alpha^{||}$ of the cutting edge across the length of the blade in the design of the tool helps to prevent the rock shear by the cutter rear edge due to the difference Δα between the cutting angle α and rear sharpening angle. Reduction of the sharpening angle from the periphery to cleave can be justified by the fact that the moment of cutting resistance at the points of the tool from the periphery to cleave is reduced because of the reduction of these points radii with respect to the tool axis.

Apart of the considered case, prevention of rock shear by the rear edge of the cutter can be implemented in the design of the drilling bit with a constant blade sharpening angle under the following condition:

$$\alpha^{|} + \alpha^{||} = \alpha^{|||} = const ,$$
(3)

where $\alpha^{|||}$ – sharpening angle of the bit cutting insert.

Based on the requirements (2) and (3) in order to achieve stable bit operation and to prevent its damage due to insufficient strength of cutting inserts, production of advanced drilling bit models should be implemented with variable front and rear sharpening angles, and in compliance with the cutter sharpening angle constancy [8]. Variation of sharpening angles of cutting insert, satisfying conditions (2) and (3), is shown in Figure 5.
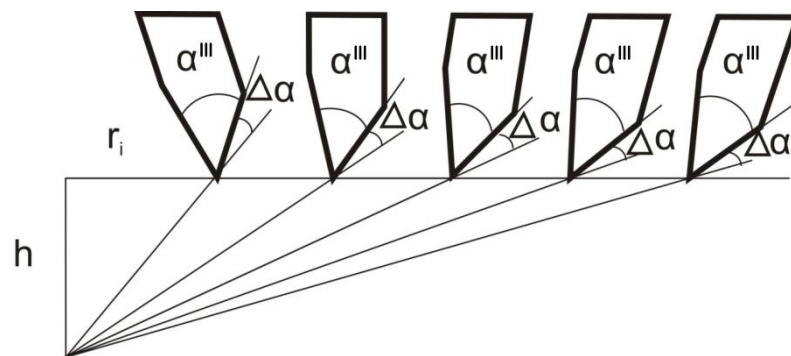
Figure 5. Variation of cutter sharpening angles from the cleave to periphery with a constant sharpening angle.

A three-dimensional view of cutting inserts with variable and constant sharpening angle is shown in Figures 6a and 6b, respectively. Figure 6 depicts: 1 – insert body, 2 – blade, 3 – insert rear edge, x-x geometric axis of the drilled borehole, arrows (a) and (b) show the insert rotation direction with respect to x-x and its advance – the deepening of the cutting insert into the borehole. Points A, B, C, D, are used to indicate the tops of the insert, forming its rear edge, L – thickness of the cutting insert, $\alpha^{\parallel}$ – the angle of its sharpening.
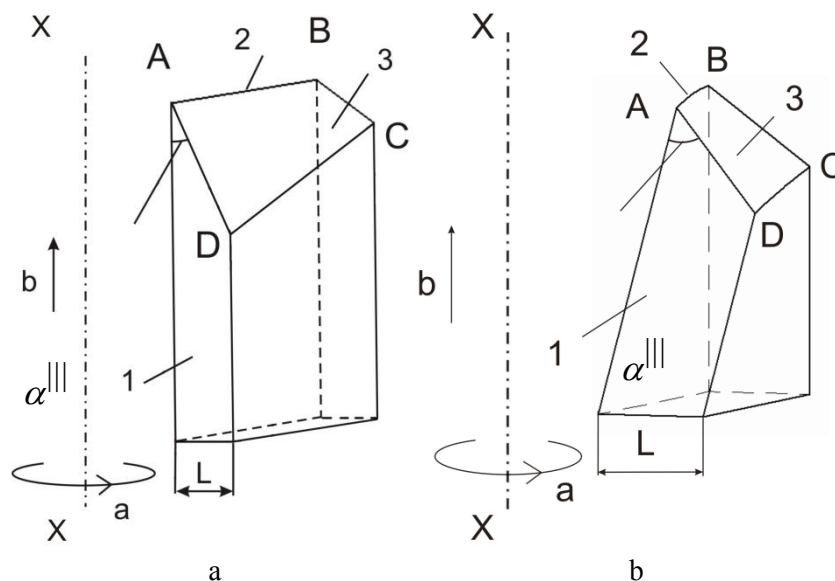

Figure 6. 3D view of cutting inserts for a drilling bit with variable sharpening angle (a) and a constant sharpening angle (b).

Production of drilling tools with the proposed geometry of the cutting inserts, requires consideration of the cutting angles depending on the advance of the drilling rod.

Table 1 shows the calculated data on variation of the cutting angle depending on the radius remoteness of blade point from the cutter axis and the value of its advance. A graphical representation of the calculated data is shown in Figure 7, from which it can be seen that the cutting angle decreases from the inner edge to the periphery, while its values rise as the advance increases.

As it was previously noted the connection between the drilling speed and number of revolutions of the drilling bit is of non-linear character because of the optimal rate of rotation of the cutter for rocks

with various strength coefficient [6]. Thus, the reserve for improvement of drilling performance may be found only in the advance increase of cutter, resulting in a significant increase in cutting angle (Table 1); and it will cause a decrease in the angle of sharpening and reduction of blade strength with the existing blade manufacturing technology.

Table 1. Variation of a cutting angle depending on the remoteness radius of a blade point from the cutter axis and the value of its advance.

Advance, mm	Radius of remoteness of the blade point, mm								
	5	7	9	11	13	15	17	19	21
3	5.46	3.91	3.04	2.49	2.11	1.83	1.61	1.44	1.30
4	7.26	5.20	4.05	3.32	2.81	2.43	2.15	1.92	1.74
5	9.05	6.49	5.06	4.14	3.51	3.04	2.68	2.40	2.17
6	10.82	7.78	6.06	4.97	4.21	3.65	3.22	2.88	2.61
7	12.57	9.05	7.06	5.79	4.90	4.25	3.75	3.36	3.04
8	14.30	10.32	8.06	6.61	5.60	4.86	4.29	3.84	3.47
9	16.00	11.58	9.05	7.43	6.29	5.46	4.82	4.32	3.91
10	17.67	12.82	10.04	8.24	6.99	6.06	5.35	4.79	4.34

The task of a substantial (in times) increase in drilling productivity, which means the drilling rate, can be expressed as follows:

$$V = h \cdot n,$$

(4)

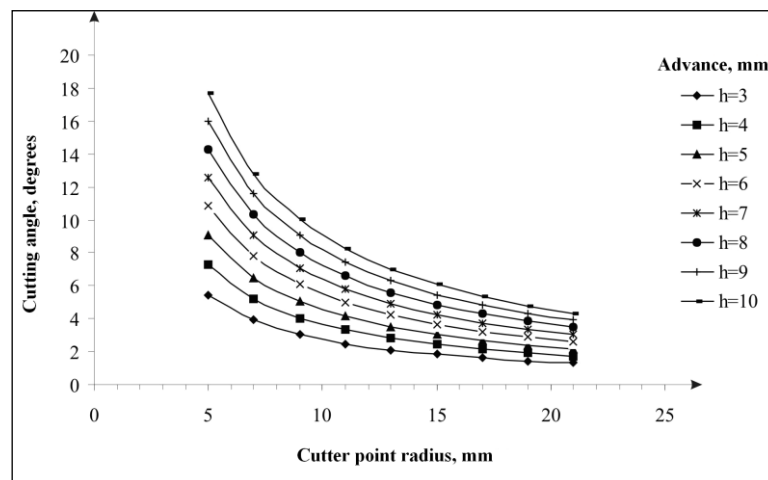where V – drilling rate, h – advance at one bit rotation, n – number of bit rotations.

Figure 7. The cutting angle of blade points depending on the distance from the rotation axis of a drilling cutter for different advance values.

Thus, the development of drilling cutters with variable front and rear sharpening angles is one of the possible solutions of the task. The difference φ between cutting angles of points of inner and peripheral parts of the blades depending on the advance value is given in Figure 8.
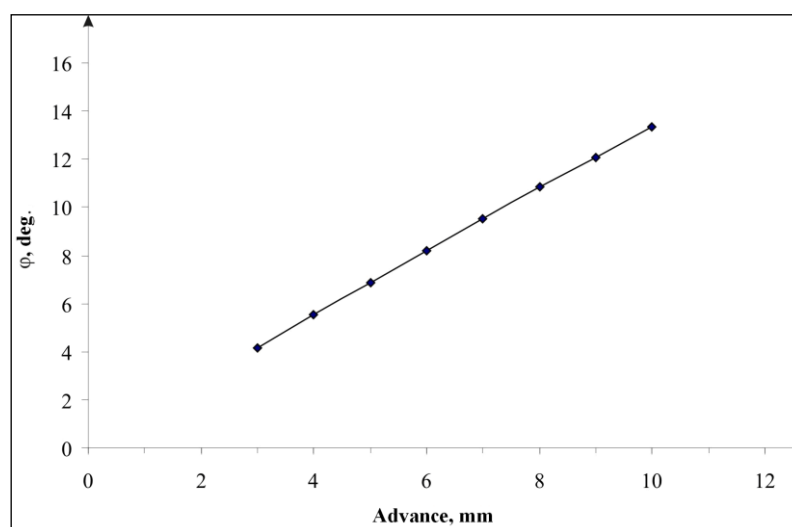
Figure 8. Dependence of cutting angle difference of inner and peripheral parts of a blade on advance value.

3. Results and discussion

Effectiveness evaluation of rock destruction by the developed tool can be carried out with the involvement of various criteria, The basic criterion is the specific power costs for rock destruction. Thus, the choice of a tool design is possible only on the basis of specific information on the lowest possible power consumption for a definite type of rock destruction. In this regard, for the research purposes the methods, which allow the power consumption during the rocks destruction to be determined quickly and with sufficient accuracy, should be used [9].

The method for determination of the power consumption, satisfying all these requirements, and the device for its implementation were developed by L.T. Dvornikov together with N.I. Naumkin [10]. The method consists in selection of samples with irregular shape, measurement of their volume followed by crushing on a hard loading device to a predetermined degree of dispersion with simultaneous removal of fractured particles of specific sizes from the crushing zone.

In accordance with this method, during the fracture of rock samples the pieces punch force and its displacement were registered. As a result the deformation and fracture diagram was recorded. The work used for rock destruction is defined as the area under the curve, and power consumption − as a specific work per initial sample volume unit.

To implement this method for determination of the power consumption several bench modifications were developed with a mechanical and hydraulic punch advancing [11-13]. The laboratory bench for determination of power consumption with a hydraulic punch advancing is shown in Figure 9.

Structurally it consists of a frame 1, perforated cup 2, where the rock samples are arranged, the punch 3 driven by a hydraulic loading cylinder 4 through a manual pump 5. The perforated cup 2 is placed on the frame 1 by means of a support 6, in which a radial-thrust bearing is placed, providing the rotation of the perforated cup 2 with handle 7 to remove the crashed rock.

The energy meter measuring unit consists of DM5007A pressure sensor that registers the force impact of the punch on the rock, and the laser displacement sensor RAS-T5-500-420A, fixing the punch position.

The measured parameters are recorded by the data collection module MSD-200 with the further plotting the deformation and rock destruction diagram by means of a specially developed software for calculation of energy consumption as a specific crashing work [14]. Thus, the work is defined as the area under the graph. A typical form of the graph, built in the software during rock sample testing, is shown in Figure 10.
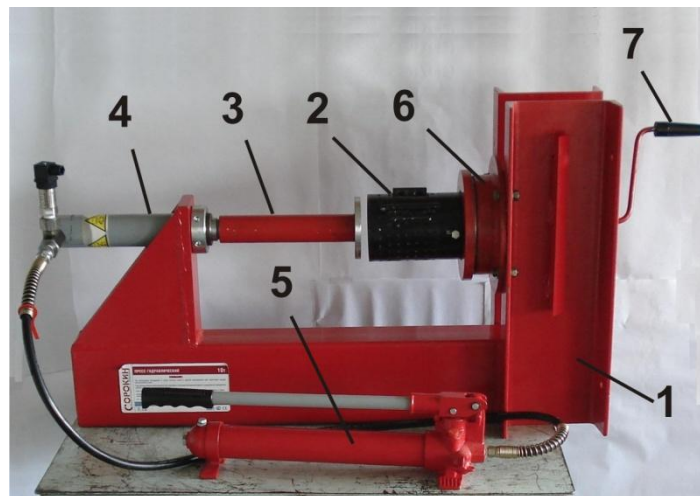
Figure 9. Laboratory bench for determining the power consumption of rock destruction with a hydraulic punch advance.
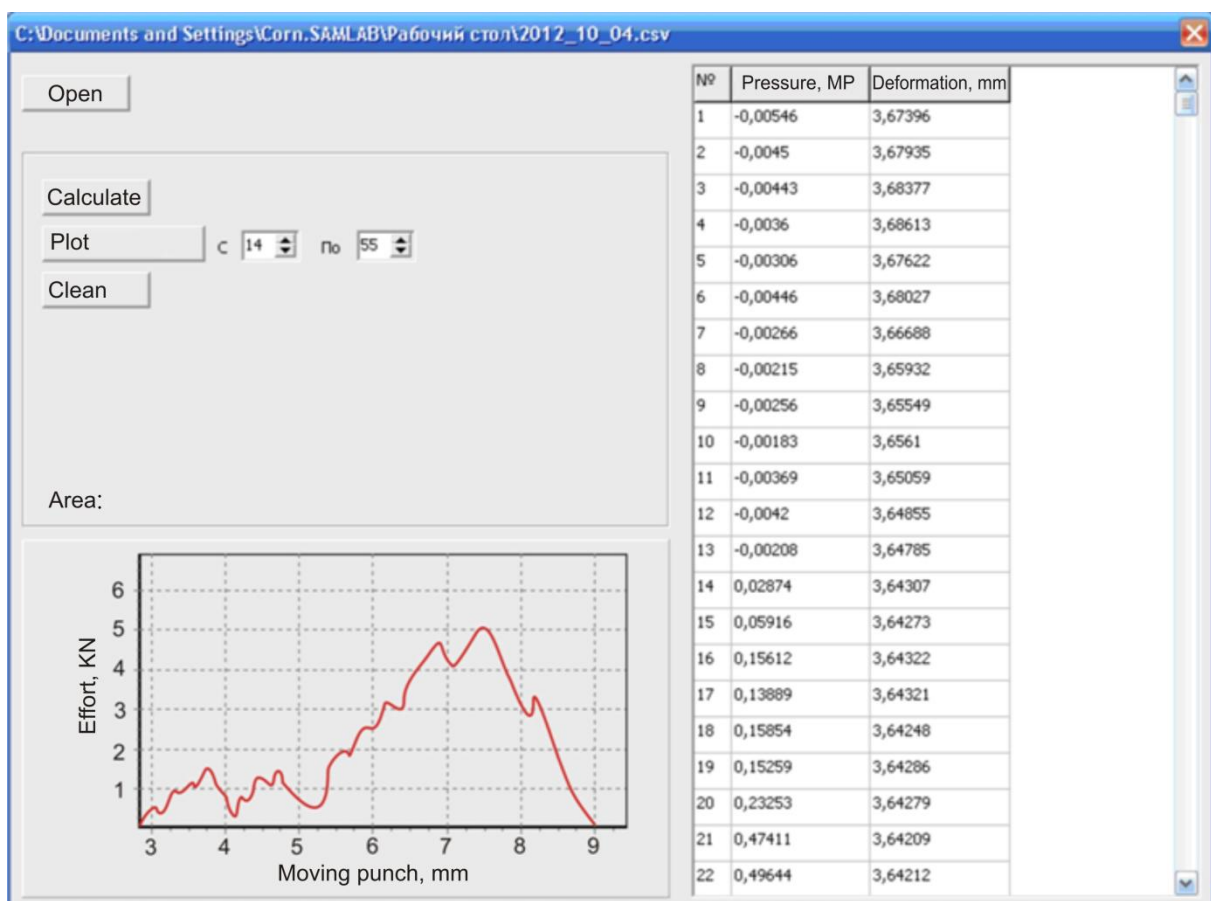

Figure 10. Deformation and rock crushing diagram plotted by the specially developed software.

As noted earlier, the use of new materials for design of cutting inserts is one of the possible ways to improve the efficiency of rock destruction. Theoretical studies at the first stage of FCP have shown

that the most promising among them are super hard composite materials on the basis of cubic boron nitride and technical diamond (PCD).

4. Conclusions

With consideration of the conducted research, the recommendations for possible use of super hard composite materials in the design of a new instrument for the effective rock destruction might be as follows:

1. It is more appropriate to use composite materials containing diamond for mining tool design, with preference given to composites with the highest thermal resistance.

2. In some cases, in particular:

- not high (relatively) hardness of the processed rock;
- high (from 400 to 900 degrees) temperature in the cutting area;
- presence of elements in the rock which are catalysts for PDC destruction (iron, nickel, cobalt), possible use of composite materials containing cubic boron nitride.

5. Acknowledgements

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