RESEARCH ON WORKABILITY OF TOOL CUTTERS WORKING UNDER CONDITIONS OF SHOCKLESS LOADS AND FRICTION

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Keywords: cutter, hard alloy, bit, back rake angle, acuity angle, rock, penetration depth, wear, unit power, wear rate.

Abstract. Hard alloy cutters of drill bit are made for working in rocks. This results in severe operation mode of bit, high wear rate and low durability. The research on geometry of hard alloy and steel cutters of bits that work under conditions of shockless loads was carried out in this work. The rationale of tungsten carbide and cobalt composition according to their hardness and robustness is provided. Medium grained and coarse grained alloys with low cobalt content were suggested to be used for reinforcement of tools, working under conditions of shockless loads. Alloys with medium and high cobalt content are recommended for reinforcement of tools employed under shock loads for drilling rocks of high hardness. Rock deformation process was identified to occur by cutting and shearing forces. The highest influence on cutting process is exerted by acuity angle and back rake angle. As a result of research peculiarity of work of cutters with positive and negative back rake angle was determined. The cutter with positive rake angle will tend to continuous deepening inside the rock under increasing rupture strength that will lead to breakdown of the cutter. That is why it is necessary to limit the depth of cutter penetration inside the rock, for example by decreasing of axial load applied to cutter of the bit. The cutter with negative back rake angle will be pushed out of the rock under increasing rupture strength of the rock. In this case it is recommended to increase axial force. The depth of cutter penetration inside the rock grows in case of increasing of axial force, decreasing of cutter width and acuity angle. If cutter is pressed in rock, the highest penetration depth under other equal conditions will be provided by the cutter with zero back rake angle, while minimal penetration depth will belong to the one with negative back rake angle. As a result of the research, dependence of depth of penetration of cutter inside the rock according to back rake angle was obtained. Indicators of wearing were identified, they include the type and properties of interacting surfaces, which are characterized by roughness of steel surface of bit cutting structure, hardness of materials in contact beetween the rock and the tool, friction mode that depends on unit pressure, movement rate, the nature of load application and the rate of interaction of working members of bit. Dependence of unit pressure on friction surfaces and slip velocity of relative movement was obtained. The mechanism of wear of steel working members of bit cutting surfaces under continuous contact with rock was determined. Fatigue cracks are identified not to occur on quenched steel.

A well in drilling stage represents mine opening of cylindrical shape, small diameter and great length. It is constructed by means of special tools without any human access inside of it and is made for extracting of liquid and gas fluids out of earth interior. The rocks surrounding a well are in complex stress condition which is governed by the weight of upperlying rocks and tectonic processes. The combination of these stresses is called rock pressure. Pores, caverns and cracks of rocks are filled with fluid which is also exposed to pressure that is called reservoir pressure. The presence of these pressures exerts considerable influence on rock resistance to rupture by rock destruction tool - bit or drilling head and affects drilling technology. The complexity of processes is explained by great well depth, alternation of beds with different reservoir pressure and by bed strikes.

Rock destruction is made by mechanical way under bit gyration by rotor from earth surface or downhole drilling motor installed directly upon the bit.

Rotation drilling by cutting hard alloy tool (fig.1) is used for drilling of soft and medium hard rocks in case of rotary drilling (with rotation of drill string) and drilling by downhole drilling motors - turbodrills, electric drills, downhole screw motors. Advantages of such an instrument include increased resistance to wear and possibility of multiple replacement of drilling tool.

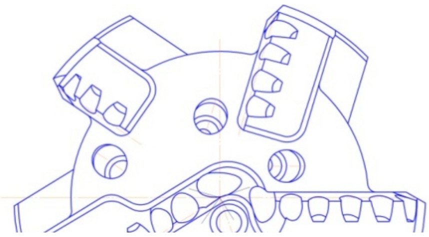


Fig. 1. Drill bit with cutters made of hard alloy

Materials for cutters in common include sintered tungsten-cobalt hard alloys of BK-type, which provide great hardness along with high wear resistance during heating up to 1000°. BK alloys almost do not incur significant deformation, they represent great compression strength but at the same time they have low flexural and tensile strength, small toughness. Sintered hard alloys consist of tungsten carbide WC and cobalt Co with different percentage. Tungsten carbide adds significant hardness and wear resistance to the alloy. Tungsten carbide is non-magnetic, pretty brittle material and has high-thermal conductivity. Cobalt - ductile and tough metal, which is a good moistener for tungsten carbide grains when melted and becomes a strong binding for them when hardened. Sintered hard alloys like BK3, BK6, BK8, BK10, BK15, BK20, BK25 (Russian State Standard GOST) are made of blend powder consisting of tungsten carbide and cobalt by means of blanking in special graphite compression molds and sintering under the temperature which is lower than melting point of carbides. Numbers in alloy grade stand for cobalt percentage, according to which alloys differ in flexural strength, density and hardness. Flexural strength of BK3 alloy is equal to 1100 MPa (minimal), while the value of BK25 alloy – 2000 (maximal). At the same time the hardest alloy is BK6 – 90 MPa (Russian State Standard GOST). The hardness of BK25 alloy is 82 MPa. Alloy hardness grows by increasing tungsten carbide content and decreasing the size of its grains. Alloys are divided into three groups according to their structure: fine grained, medium grained, coarse grained. In case of increasing cobalt percentage and graininess, toughness of alloy grows. Tensile strength of hard alloy cutters can be considerably increased by reinforcement, for example, by cooling in nitrogen or diamond grinding. Diamond grinding removes defective layer from cutter surface. This sufficiently increases flexural strength of an alloy with toughness growth being equal to 20-30% and shock durability being 10 times larger.

Taking into account the main physical-mechanical properties, medium and coarse grained alloys with low cobalt content are employed for reinforcement of tools working under conditions of shockless loads, i.e. drilling tools for rotation drilling. Alloys with medium and high cobalt content are recommended for reinforcement of tools employed under shock loads, i.e. drilling tools for percussion-rotary drilling and roller-cutter bits made for drilling rocks of high hardness. These alloys have the greatest robustness, but they are less wear resistant.

Rock deformation process occurs by applying cutting and shearing forces: P_{oc} – axial force, F_p – cutting force (fig. 2). Every cutting element of a bit is considered as a single cutter with the following parameters: α – cutter acuity angle; $\gamma_п$ – back rake angle of a cutter; $\gamma_з$ – relief angle of a cutter; β_p – cutting angle. The following shapes of cutters are possible: I – with positive back rake angle; II – with negative back rake angle; III – self-sharpening cutter [1]. Cutting is made by continuous separation of plastic rock or chip by cutting edge of cutter pressed against well bottom; shearing - periodical separation of rock splinters from well bottom by the cutter pressed against the rock with sufficient axial force or by applying shock pulse to the cutter; simultaneous cutting-shearing is possible by separation of big parts of rock by shearing or tearing by front face of cutter with following cutting of small protrusions until new spalling occurs.

Work efficiency of cutter mainly depends on cutter acuity angle α, back rake angle of a cutter $\gamma_п$, the angle of rotation of cutters, their number and their position relatively to each other. Angle α is chosen according to the nature of drilled rocks: the harder rock is, the greater angle is. As for rocks of medium hardness, α = 90° is rational, while for soft ones – 75–80°.

Under action of axial force P_{oc} cutter penetrates inside the rock to the depth h. Destruction of the rock occurs under action of the force F_p, which originates from rotational torque. During penetration inside a rock every cutter of drilling tool makes a path along helix trajectory with well radius R and helix lead S.

At the first moment of cutter penetration without rotation inside elastoplastic rock, its bearing failure and squashing by back face of cutter occur. At this time some part of destructed rock extrudes from under the cutter as finely split mass. Then under action of axial force penetration occurs along inclined surface of back face of cutter and the rock is destructed by front face of the cutter when it moves frontwards. In this case the rock is split from the front and the sides of a cutter. Under the back face of the cutter the layer of pressurized and squashed rock occurs. The volume of destructed rock exceeds the volume of intruded part of the cutter and the more brittle rock is and the higher axial force is applied, the greater this difference is.

The nature of rock destruction has a cyclic character, spalling of rock in big volume occurs first, then small particles are separated with following energy accumulation (the cutter stops, abutting in layer of rock that has not been destructed) and new spalling of great volume of rock. In this case jerking and shutdowns occur during destruction.

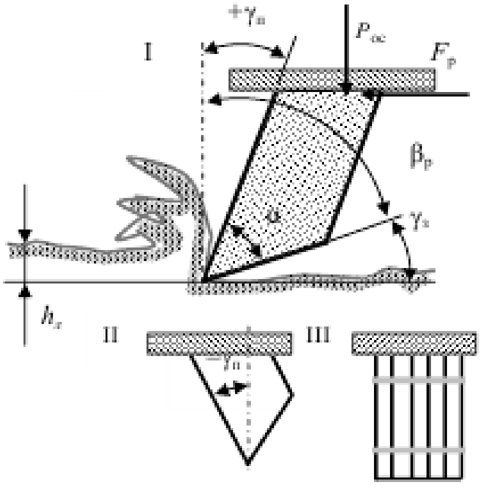


Fig. 2. The scheme of parameters of cutting structure of hard alloy bit

As a result of the research, dependence of depth of penetration of cutter inside the rock according to $\gamma_{\text{п}}$ angle was obtained

$$h = \frac{0{,}5F_p\left(\cos\gamma_n \pm \sin\gamma_n f\right)\cos\gamma_n}{pltg\alpha\left(2f\cos\alpha + \sin\alpha - f^2\sin\alpha\right)\left(1 + tg\varphi\right)}, \tag{1}$$

where φ – internal friction coefficient, p – rock hardness, f – coefficient of friction of cutter on rock. A plus sign in numerator is put when $\gamma_{\text{п}} \geq 0°$, minus sign is used when $\gamma_{\text{п}} < 0°$.

Equation (1) indicates that depth of penetration of cutter inside the rock grows by axial force increasing, decreasing of cutter width and acuity angle α as well as in case of smaller values of rock hardness, coefficient of external friction of cutter on rock, internal friction coefficient. If cutter is pressed in rock, the highest penetration depth under other equal conditions will be provided by the cutter with zero back rake angle, while minimal penetration depth will belong to the one with negative back rake angle. The conditions of application of cutters with positive back rake angles are limited by drilling the softest rocks. The cutters with zero and negative back rake angles are used for drilling rocks of soft and medium hardness, with cutters with negative back rake angle being preferred to use for drilling harder rocks as the cutter inclination to opposite side from movement direction reduces dynamic loads applied to the cutters and the tool proportionally to sin $\gamma_{\text{п}}$. With increasing of positive back rake angle less forces are required to destruct the rock to the given depth. On the contrary, with an increase in negative back rake angle destruction forces for the given depth must grow.

As a result of research peculiarity of work of cutters with positive and negative back rake angle was determined. The cutter with positive rake angle will tend to continuous deepening inside the rock under increasing rupture strength that will lead to breakdown of the cutter. That is why it is necessary to limit the depth of cutter penetration inside the rock, for example by decreasing of axial load applied to cutter of the bit. The cutter with negative back rake angle will be pushed out of the rock under increasing of rupture strength of the rock. In this case it is recommended to increase axial force.

Therefore, cutters with positive back rake angles are recommended to use only for drilling soft rocks by two-blade or three-blade drill bits of cutting-shearing action. The cutters with negative and zero back rake angles are employed for drilling both soft and medium hard rocks. All cutters for drilling hard and tough rocks have negative back rake angles. In addition, the value of negative back rake angle must grow as rock hardness increases.

The dependence of calculation of penetration depth of a cutter taking into account it's wearing looks the following way:

$$h = \frac{0{,}5F_p\left(\cos\gamma_n \pm \sin\gamma_n f\right)\cos\gamma_n}{pltg\alpha\left(2f\cos\alpha + \sin\alpha - f^2\sin\alpha\right)\left(1 + tg\varphi\right)} - \sqrt{\frac{qF_p f v_p t}{ltg\alpha}}, \tag{2}$$

where q – wear magnitude, v_p – rate of cutting-shearing of the rock, mps, t –time.

In the operation process rotation drilling causes wear of drill bit cutting structure resulting in change of drill bit shape and size. Having reached ultimate wear magnitude, the tool becomes unappropriate for further exploitation and it requires reconstruction or replacement.

The process of wear of hard alloy cutters during drilling is characterized by the presence of zones (fig.3):

Zone I - intense wear of sharp edges of cutters during which stable worn place is formed. Penetration speed decreases while volumetric destruction work grows.

Zone II - steady-state wear that occurs along the main drilling interval. Wear occurs due to detrition, contact pressures, penetration depth and volumetric destruction work are constant

Zone III - fatigue or temperature wear is accompanied by sudden decrease in penetration depth and increase in volumetric destruction work. The highest temperature occurs in the centre of site of cutter blunting. Having reached maximal value, wear intensity abruptly rises with creation of crack pattern. In this case drilling becomes unproductive. That is why work of drill bit cutters in zone III is impermissible.

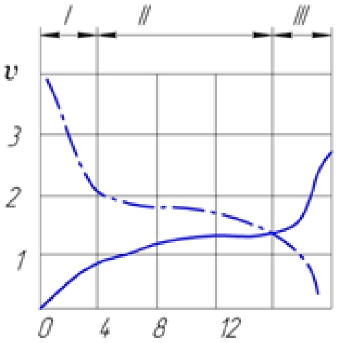


Fig. 3. Dependence of penetration rate υ meter per hour (axial line) and wear meter (base line) of drill bit cutters on drill footage

Rational location of cutters in drill tool would be the one which guarantees occurrence of free surfaces in the process of rock destruction, it leads to increase in penetration rate. If wear intensity ω is introduced as wear W per unit of work of friction forces A_T,

$$\omega = \frac{W}{A_T} = \frac{W}{fPL}, \qquad (3)$$

where f – friction coefficient, P – normal loading, L – friction path.
then wear per time unit t_0 will be called wear rate a; $a = W / t_0$

It was established that wear indices depend on great amount of simultaneously acting factors: type and properties of interacting surfaces (roughness, crookedness, hardness of materials), friction mode (unit pressure, movement rate, the nature of load application and the rate of interaction of working members of bit), type and properties of environment (lubricating and cooling ability).

While blade instrument during metal cutting must work in given mode with minimal energy losses due to friction, rock destruction tool is used for concentrated energy realization by work surfaces of cutting structure of drill bits during interaction with rock. It results in severe operation mode of drill bit, high wear rate and low durability.

Cyclic interaction of drill bit cutting structure elements is characterized by unit power N

$$N = A_1 \nu / F \qquad (5)$$

where A_1 – work that is made by a single element of drill bit cutting structure for one interaction with rock, ν – interaction frequency, F – the square of work surfaces of one element of cutting structure of drill bit.

As a result of the research it was identified that values of ν, N, q, $t_к$ can cause structural and phase transformations in surface layers of metal of drill bit cutting structure and govern thermal mode in zone of contact between metal and rock.

The research was conducted by employing drill bit with diameter equal to 295,3 mm, with impact velocity υ_y being 1,5 – 2,4 mps. Slip velocity υ was 2 mps, rate of supply of cooling q of hydrocarbon liquid was equal to 10 mps, contact time reached $t_к$ 10 – 50 ms with interaction frequency being ν 25 – 30 s^{-1}, while unit power N ranged from 5,0 to 8,0 W / mm^2. It was established that under changing unit power N to 8,0 W / mm^2 the following types of wear can be distinguished (fig. 4).

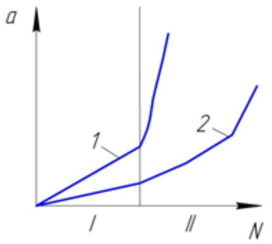


Fig. 4. Dependences of wear rate of drill bit on unit power during drilling 1 – terrigenous rocks, 2 – crystalline rocks. I , II – wear areas

Under unit power N lower than 4,0 W/mm^2 wear area I is formed. This wear area is typical for normal accident-free work of a tool that works with low rotation rate and small unit loads. In this area wear rate a of cutting structure of drill bit corresponds to directly proportional dependence on unit power N.

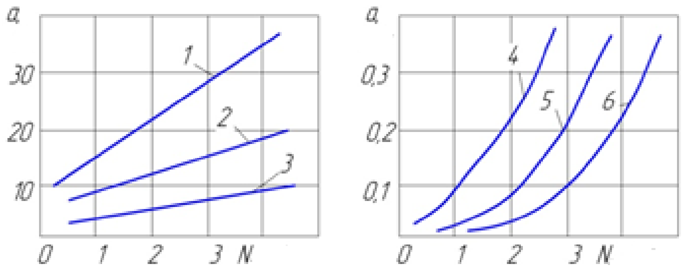
If during drilling terrigenous rocks wear rate increases or linear dependence between a and N disrupts, what usually happens while drilling crystalline rocks, tool starts working in II wear area.

Wear of drilling tool during friction was noticed to depend on rates of relative movement of interacting surfaces and unit pressures on them. If the rate of relative movement of interacting surfaces is low but unit pressure is high, this is wear with grasp of the first kind with occurrence of scuffing on metal. Under small unit pressures and slip velocities oxidative wear with flaking of metal occurs. And on the contrary, under high slip velocities and unit pressures we obtained occurrence of wear with grasp of the second kind or temperature wear with creation of phenomena of tempering, recrystallization and secondary quenching of surface layers of metal.

As unit power increases in the process of drill bit work, i.e. as loading grows under the constant rotation rate, ultimate stress state occurs [4]. The same power N can be obtained during wear tests by varying ratio of unit pressure to slip velocity that allows getting different rates of rock destruction and types of destruction (fig. 2). As a result of the research,dependence between unit pressure on friction surfaces p and slip velocity of relative movement υ_c was identified.

$$N = f \cdot p \cdot \upsilon_c \qquad (6)$$

Proceeding from equation (5), decrease in slip velocity under the same unit power results in increase in loading on work surfaces of drill bit cutting structure, which causes growth of shearing stress. Reducing slip velosity decreases critical power under which disruption of stability of work surface of a drill bit cutting structure occurs. In case of high speedwear modes ($\upsilon \geq 1,4$ mps) disruption of stability is obtained under lower loads than in case of low speed modes($\upsilon = 0,2$ mps) (fig. 4). Wear area II is likely for work of elements of drill bit cutting structure. The work of drill bits under high speed or low speed modes of drilling has low efficiency.



a) b)

Fig. 5. Dependences of wear rate *ŕ* (mm/h) on unit power *N* (W/mm^2) for steel 20ŐÍ3Ŕ (GOST - Russian State Standard) in the II area: ŕ) terrigenous rocks, b) crystalline rocks, 1 – sandstone, 2 – siltstone, 3 – argillite, 4 – dolomite, 5 – limestone, 6 – anhydrite

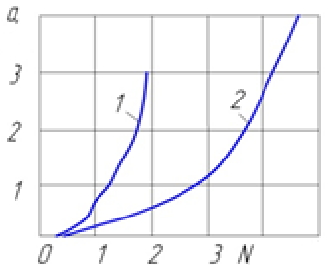


Fig. 6. Dependences of wear rate *ŕ* îň on unit power *N* for steel 20ŐÍ3Ŕ (GOST - Russian State Standard) during dolomite destruction under conditions of stability disruption:
1 - low speed mode (ő = 0,2 mps),
2 – high speed mode (ő = 1,4 mps)

In the area I process of wear along it's depth doesn't go out of borders of oxide films, that occur on the surface of quenched steel. Multiple action of rock roughness applied to them causes fatigue snuffing of these films. Worn surface gets polished and causes decrease in roughness of steel of work surfaces of drill bit cutting structure (fig.6). During friction with terrigenous rocks we obtained scratching of steel work surfaces of cutting structure of drill bit by favourably located separate quartz grains, which hardness is higher than the hardness of quenched steel. Therefore, wear rate of steel work surfaces of bit cutting structure by terrigenous rocks is considerably higher than by carbonate or sulphate crystalline rocks.

Increasing *N* up to value corresponding to transfer from area I to area II leads to occurrence of zone of decreased hardness of work surfaces of drill bit cutting structure which is connected to tempering of metal due to heat and friction (fig.5, *a*).

Heating and thermal weakening of steel increase wear rate due to growth of rate of oxidizing process and facilitating deformation of its surface. Dark spots and tears occur on steel surface. Especially dramatically the rate of wear against sandstones increases as thermally weakened surface is easily deformed and scratched by quartz shatters (fig.6).

In the area of $N \geq 1$ W/mm^2 tears on the steel of the work surfaces of drill bit cutting structure transfer into pattern of cracks of fatigue nature during friction with carbonate and sulphate rocks. During friction with terrigenous rocks cracks do not occur due to high wear rate.

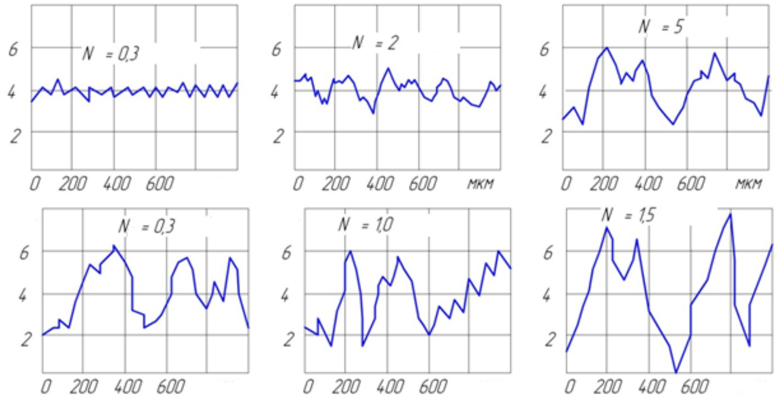
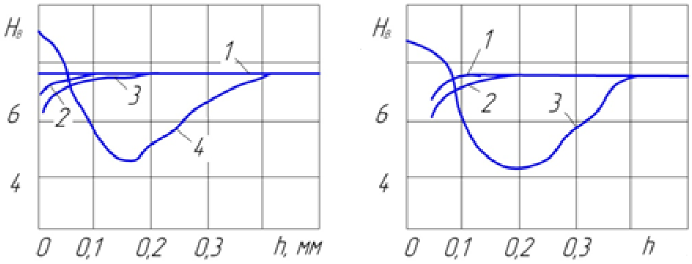


Fig. 7. Profilograms of steel surface after wearing against limestone (upper row microns), sandstone (lower row W/mm^2).

Big depth and degree of thermal weakening under high values of *N* make it possible to deform steel work surfaces of drill bit cutting structure by grains of carbonate and sulphate rocks that have lower hardness. Roughness of work surface of drill bit increases (fig.5).

Repeated deformation of steel causes fatigue destruction both brittle surface films and metal which is separated as small flakes. During friction with sandstones cutting of metal in form of chip is obtained.

Thermal influence on metal causes both tempered metal structure formation in form of troostite and occurrence of white phase, which accounts for high microhardness of surface layers of metal under $N \geq 3$ W/mm^2 (fig. 7). White phase occurs during secondary quenching and intense repeated deformation of work surface of drill bit cutting structure [5]. As white phase develops, spalling and flaking of separate places of repeatedly deformed steel surface occur along with formation of pattern of surface cracks. Thermaly weakened metal is flattened on harder base, creeping and spalling along the edges of surface cracks. Rock grains, intruding into surface of steel work surfaces of drill bit armouring, block it and under certain thermal weakening they can cause surface shearing that will lead to disruption of stability of metal surface. In this case catastrophic growth of wear rate of steel work surfaces of drill bit armouring is observed.



a) b)

Fig. 8. Graph of change of microhardness H_b (HPa) of steel grade 20XH3A along the depth of work surface after work in limestone under unit power (W/mm^2) equal to: a) 1 – 0,3; 2 – 0,6; 3 – 2,1; 4 – 4,8; b) in chisel teeth, 1, 2, 3 – numbers of rolling-cutter teeth row.

The change of microstructure and hardness of metal in surface layers of cutting structure of drill bit under heat friction action allowed us to specify the distribution of microhardness in elements of drill bit armoring (fig. 8, b). Comparison of microhardness shows that dependences are similar.

Research that has been carried shows that the type of abrasive wearing during friction with rocks and in process of their destruction depends on modes and conditions of their work.

All in all, the research on geometry of hard alloy and steel cutters of bits that work under conditions of shockless loads was carried out in this work. The rationale of tungsten carbide and cobalt composition according to their hardness and robustness is provided. Medium grained and coarse grained alloys with low cobalt content were suggested to be used for reinforcement of tools, working under conditions of shockless loads. Alloys with medium and high cobalt content are recommended for reinforcement of tools employed under shock loads for drilling rocks of high hardness.

Rock deformation process was identified to occur by cutting and shearing forces. The highest influence on cutting process is exerted by acuity angle and back rake angle. As a result of research peculiarity of work of cutters with positive and negative back rake angle was determined. The cutter with positive rake angle will tend to continuous deepening inside the rock under increasing rupture strength that will lead to breakdown of the cutter. That is why it is necessary to limit the depth of cutter penetration inside the rock, for example by decreasing of axial load applied to cutter of the bit. The cutter with negative back rake angle will be pushed out of the rock under increasing of rupture strength of the rock. In this case it is recommended to increase axial force. The depth of cutter penetration inside the rock grows in case of increasing of axial force, decreasing of cutter width and acuity angle. If cutter is pressed in rock, the highest penetration depth under other equal conditions will be provided by the cutter with zero back rake angle, while minimal penetration depth will belong to the one with negative back rake angle. As a result of the research, dependence of depth of penetration of cutter inside the rock according to back rake angle was obtained.

The mechanism of wear of drill bit cutting structure was considered under cyclic interaction of its work surface with the rock. The mechanism of wearing of steel work surfaces of drill bit cutting structure was identified during constant contact with the rock. It was identified that fatigue cracks do not occur on the surface of quenched steel of drill bit armoring.

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