

ПОВЫШЕНИЕ ЭФФЕКТИВНОСТИ ПРОЦЕССА СКОЛООБРАЗОВАНИЯ ПРИ УДАРНО-ПОВОРОТНОМ ВОЗДЕЙСТВИИ ДОЛОТА НА ГОРНУЮ ПОРОДУ

А.А. Гринько¹, Н.И. Сысоев¹, Д.А. Гринько¹

¹ Южно-Российский государственный политехнический университет (НПИ) имени М.И. Платова, Новочеркасск, Россия, e-mail: nextdingo@mail.ru

Аннотация: Представлен анализ известных способов бурения. Рассмотрены схемы сил, действующие на буровой инструмент, и осциллограммы процесса изменения силовых показателей при бурении породы различными способами. На основании сравнительного анализа предложено по-новому осуществлять силовое воздействие на буровой инструмент для повышения эффективности бурения, а именно внедрение лезвия долота в породу по винтовой траектории, шаг которой подобран из условия наилучшего сколообразования. Математическим и физическим моделированием внедрения лезвия долота в поверхность породного массива в зависимости от угла приложения ударной нагрузки установлено наличие существенного влияния данного параметра на эффективность сколообразования в породном массиве. На специально разработанном стенде для изучения процесса внедрения долота с поворотом в породный массив подтверждено более эффективное использование энергии единичного удара на формирование скола породы, а не только дробления. Представленные результаты математического и физического моделирования внедрения лезвия долота в поверхность породного массива в зависимости от угла приложения ударной нагрузки подтверждают целесообразность продолжения исследований по установлению оптимального угла приложения и энергии ударной нагрузки в зависимости от физико-механических свойств породы и определения влияния геометрии бурового инструмента на эффективность бурения.

Ключевые слова: бурение, долото, винтовая траектория, породный массив, эффективность сколообразования, математическое моделирование, физическое моделирование, угол приложения ударной нагрузки.

Благодарность: Исследование выполнено при финансовой поддержке РФФИ в рамках научного проекта № 19-35-90079

Для цитирования: Гринько А. А., Сысоев Н. И., Гринько Д. А. Повышение эффективности процесса сколообразования при ударно-поворотном воздействии долота на горную породу // Горный информационно-аналитический бюллетень. – 2020. – № 9. – С. 102–115. DOI: 10.25018/0236-1493-2020-9-0-102-115.

Improving shearing efficiency of percussion rotary drill bits

A.A. Grinko¹, N.I. Sysoev¹, D.A. Grinko¹

¹ Platov South-Russian State Polytechnic University (NPI), Novocherkassk, Russia, e-mail: nextdingo@mail.ru

Abstract: The article presents the analysis of well-known drilling methods. The scheme of forces on a drill tool and the oscillograms of varied impact force in different-type drilling in rocks are considered. Based on the comparative analysis, a new approach to force impact on drilling tool is proposed to increase drilling efficiency, namely, to make a drill bit penetrate rocks along a helical path at a pitch selected from the condition of the most effective shearing. The mathematical and physical modeling of drill bit penetration in rock mass depending on the angle of impact load application reveals significant effect of this parameter on the efficiency of shearing. The studies into the process of drill pit penetration with rotation in rock mass on a specially designed test bench prove the more efficient use of the unit impact energy for shearing. The presented results of the mathematical and physical modeling of drill bit penetration in rock mass depending on the angle of impact point at expediency of further research to optimize impact angle and energy as function of physical and mechanical properties of rocks and for determining the effect of drilling tool geometry on drilling efficiency.

Key words: drilling, drill bit, helical path, rock mass, shearing efficiency, mathematical modeling, physical modeling, impact load angle.

Acknowledgments: The study was supported by the Russian Foundation for Basic Research, Project No. 19-35-90079

For citation: Grinko A. A., Sysoev N. I., Grinko D. A. Improving shearing efficiency of percussion rotary drill bits. *MIAB. Mining Inf. Anal. Bull.* 2020;(9):102-115. [In Russ]. DOI: 10.25018/0236-1493-2020-9-0-102-115.

Introduction

In view of the current increase in drilling activities and the need for less energy-intensive methods of rock destruction with a drilling tool, it is required to improve efficiency of drilling. Drilling efficiency is usually estimated by the rate and energy intensity of rock destruction. The drilling rate is estimated by the drilling tool penetration per unit time and depends on such factors as rock strength, geometry of the rock cutting tool and the selected operating modes. The energy intensity of the drilling process is estimated by the amount of energy spent per meter of drilling and primarily depends on the ratio of crushed and sheared rocks. In formation of large-size shears, the energy intensity of destruction will be less than in formation of small-size shears with increased crushing. For a less energy-intensive process of rock destruction, it is necessary to select optimal operating parameters for drilling in specific conditions. This is achieved

with the help of adaptive control systems and software algorithms that consider environmental conditions, as well as using more advanced schemes of force impact on drilling tool [1–3]. Lower specific energy consumption often leads to higher drilling rates.

Comparative analysis of drilling methods

At present, drilling employs various tools and methods of force impact on rocks to be broken. The volumetric or surface destruction of rocks is defined by the nature of rock deformation at the contact with drilling tool [4]. In volumetric damage, the pressure on the rock–drilling tool interface exceeds the temporary indentation resistance. While in surface destruction, there is no penetration in rock since the specific contact pressure of the tool edge on rock will be less than the rock indentation hardness. Rock destruction occurs due to abrasion and is accompanied

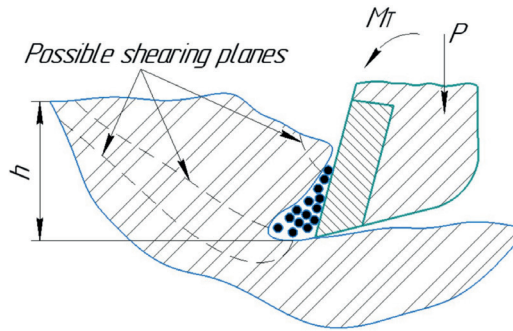


Fig. 1. Diagram of forces acting on drill bit in rotary drilling

Рис. 1. Схема сил, действующих на резец при вращательном способе бурения

by intense wear of drilling tool and by increased energy consumption of fracture. It follows from the foregoing that the efficiency of drilling to be increased needs long as possible operation of the tool in the field of volumetric fracture.

Rocks can be fractured using such methods of mechanical destruction as cutting, impact rupture and cutting with simultaneous impact effect. Accordingly, rotary drilling, percussive drilling and rotary-percussive drilling modes are distinguished.

In rotary drilling (Fig. 1), rock is fractured in continuous rotation and translational movement of the drilling tool under constant thrust force P and torque M_T . The tool moves along a helical line with a relatively small pitch, and the tool edges or lips break the rock to a depth h . This means that the rotary drilling efficiency is determined by the zones of volumetric and surface fracture in rocks. Longer operation of the tool in the zone of volumetric fracture promotes higher efficiency of rotary drilling.

To analyze and compare the change in the force impact on the drilling tool over a period t for various methods of impact effects, the oscillograms of drilling were obtained. Fig. 2 shows the oscillograms of the thrust force P and torque M_T in various drilling methods. It is seen in Fig. 2a that the drilling tool is subject to the constant thrust P and the jumping torque M_T . The

jumps in the torque are associated with different forces required for shearing different volumes of rocks in drilling.

The rotary percussive method (Fig. 3) is a combination of cutting with simultaneous impact loading of the drilling tool. In rotary percussive drilling, a continuously rotating drill bit, the edge of which has the form of an asymmetric wedge, penetrates a rock to a depth h under the action of the significant thrust P and an impact momentum P_{im} . The shock load contributes to a more effective penetration of the cutting edge of the drill bit in rock, and the high torque M_T provides volumetric shearing of rock by the front face of the drilling tool [5].

In rotary percussive drill bits, the power of the rotator significantly exceeds the power of the shock mechanism. The rotary percussive drilling method is the most effective in rocks with Protodyakonov's hardness factor $f = 6 - 12$.

The oscillogram of percussive drilling in Fig. 2b shows that the change in the impact forces over a period t is similar to the oscillogram of rotary drilling. However, a distinctive feature is the presence of impact momentum P_{im} , which is applied to the drilling tool at a certain frequency.

In percussion rotary drilling (Fig. 4), the drill bit is affected by the similar forces as in the above-described method of drilling, but their ratio is fundamentally

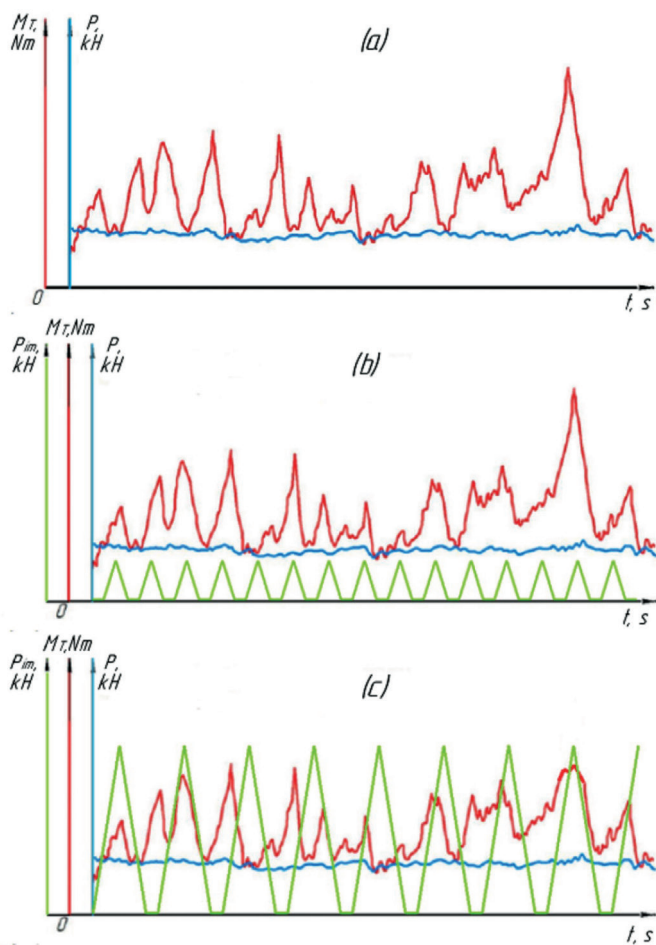


Fig. 2. Oscillograms of thrust force P and torque M_τ : (a) rotary drilling; (b) rotary percussive drilling; (c) percussive rotary drilling

Рис. 2. Осциллограммы осевого усилия P и крутящего момента M_τ : при вращательном бурении (а); при вращательно-ударном бурении (б); при ударно-вращательном бурении (в)

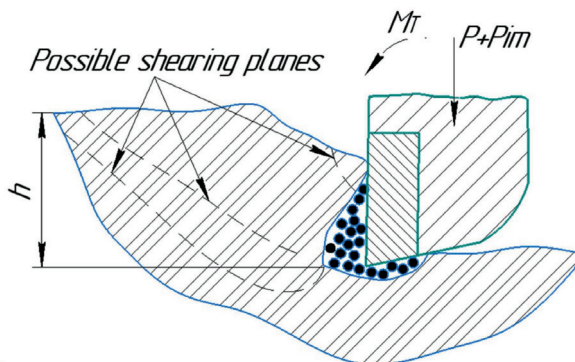


Fig. 3. Diagram of forces on drill bit in rotary percussive drilling

Рис. 3. Схема сил, действующих на буровой резец при вращательно-ударном способе бурения

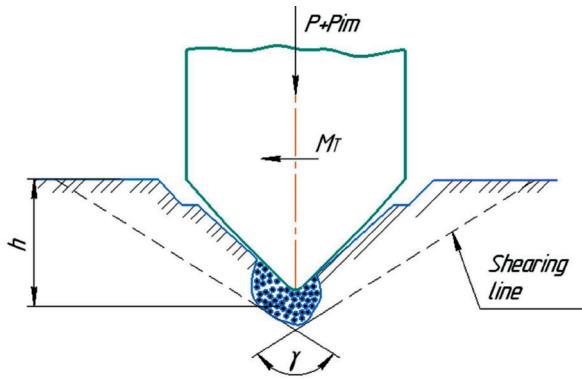


Fig. 4. Diagram of forces on drill bit in percussion rotary drilling: P – thrust; P_{im} – impact momentum; M_T – torque; h – penetration depth; γ – rake angle

Рис. 4. Схема сил, действующих на долото при ударно-вращательном способе бурения: P – осевое усилие; $P_{уд}$ – ударная нагрузка; $M_{кр}$ – крутящий момент; h – глубина внедрения в породу; γ – угол развала борозды

different. Penetration in rock to a depth h and bulk rock fracture is due to the impact momentum P_{im} . The constant torque M_T rotates the drill bit and cleans up the face from crests of neighbor indents, while the constant and relatively low thrust only presses the drilling tool to the face [5].

The analysis of the percussion rotary drilling oscillogram in Fig. 2c shows that the process of the force change during t is identical to the oscillogram of rotary percussive drilling, except for a higher value of P_{im} required for additional penetration of the drilling tool in the axial direction and for destruction of the bulk volume of rock.

The value of energy supplied to the rock-breaking tool in rotary percussive and percussion rotary drilling is always greater than in rotary or percussive drilling, and the nature of rock destruction can be both volumetric and surface depending on the ratio of specific static and dynamic loads acting simultaneously, and on the hardness of rock mass in its complex stress state. This means that increase in efficiency of percussion rotary and rotary percussive drilling requires volumetric fracture process to be maintained for a longer period of time.

In percussion rotary drilling (Fig. 5), rock is destroyed by the impact P_{im} ap-

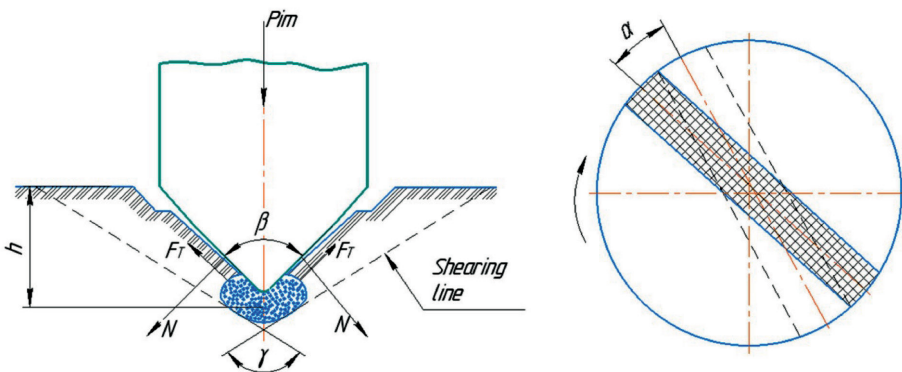


Fig. 5. Drill bit-rock interaction in percussion rotary drilling: α – angle between impacts; β – tool angle

Рис. 5. Схема взаимодействия долота и разрушаемого массива при ударно-поворотном бурении: α – угол между ударами; β – угол заострения бурового инструмента

plied along the axis of the drill bit at a certain frequency, and by turning the tool between impacts by the angle α . Percussion rotary drilling creates a complex stress state in rock mass. Under the action of the compressive stresses, a compacted core of crushed rock is formed under the destructive face of the tool, and under the action of the shear stresses from the forces N , shearing of rocks takes place at an angle $\gamma > \beta$ in the direction of the open plane. The drill bit penetrates rock to a depth h governed by the unit impact energy of P_{im} .

The main factors affecting the efficiency of percussion rotary drilling are the energy and frequency of impact load applied to the tool, as well as the tool turn angle α between impacts.

Fig. 6 shows the dependence of the penetration depth h of the drilling tool edge on the angle of the impact load during percussion rotary drilling for t . It is seen from the diagram that the penetration depth of the drilling tool edge increases in direct proportion to the percussive load period t_p . The impact load angle α is zero since the drilling tool penetrates without turning relative to its axis.

Then, the tool returns to its zero position during the time t_{zr} and rotates at an angle $\alpha = 15 - 20$ degrees out of the contact with rock during t_i . After that, the rock-drilling tool interaction cycle is repeated.

Study concept

An increase in the efficiency of percussion rotary drilling is achieved by penetration of the drill bit in rock along a helical path at a pitch sufficient to ensure deviation of the vector of the impact load on the drill bit from the axis by an angle of the most efficient shearing.

Fig. 7 shows the diagram of the drilling tool-rock interaction to explain this idea. It is obvious that the combination of number of shears and frequency of impacts should theoretically coincide in phase, i.e.,

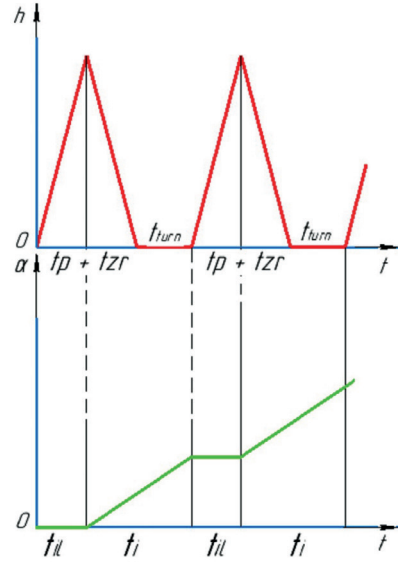


Fig. 6. Penetration depth h of drilling tool versus impact load angle α in percussion rotary drilling during time t : t_p – percussion loading duration; t_{zr} – zero-point return of drill bit; t_{turn} – turning time; t_{il} – impact load time; t_i – idle rotation time of drilling tool

Рис. 6. Зависимость глубины внедрения h лезвий бурового инструмента от угла приложения ударной нагрузки α при ударно-поворотном бурении за время t : t_y – время действия ударно-поворотной нагрузки; t_b – время возврата инструмента в исходное положение; $t_{нов}$ – время, затрачиваемое на поворот инструмента; $t_{пн}$ – время, затрачиваемое инструментом на ударную нагрузку; $t_{хп}$ – время холостого поворота бурового инструмента

the composition of the thrust and impact load vectors will have a determining influence on increase in efficiency of rock breaking by the cutting edge of the drilling tool. However, this process is unpredictable and directly uncontrollable. At the same time, it is obvious that control over the direction of the vector of P_{im} and its value can improve the shearing efficiency and increase the penetration rate as a result. Applying the impact load P_{im} to the tool with simultaneous rotation can both increase the energy transferred to rock for destruction and ensure its targeted action on the face.

Thus, the proposed method of drilling differs from the regular percussion rotary

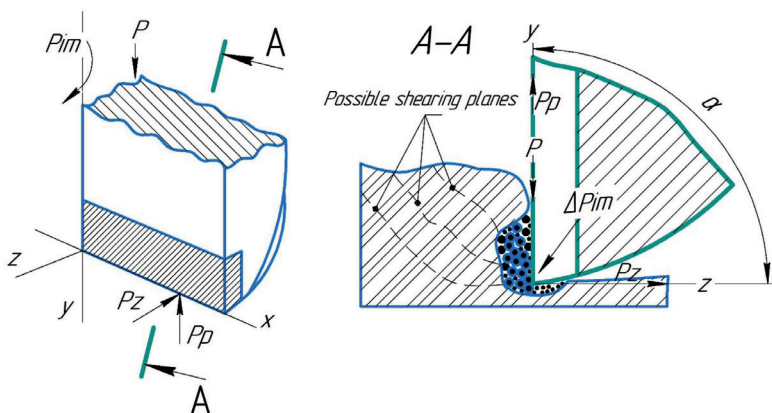
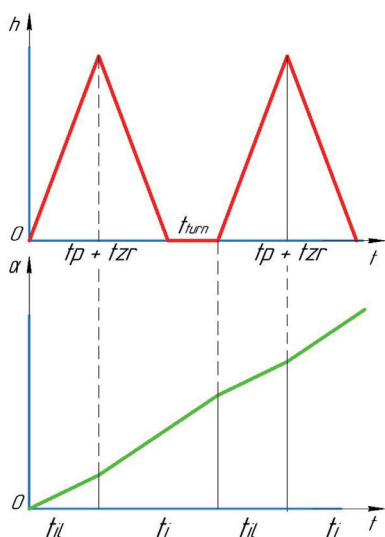


Fig. 7. Scheme of forces on drilling tool in its penetration in rock along helical path: P – thrust; P_{im} – directional impact load; P_p – penetration resistance; P_z – cutting resistance; α – possible domain of impact load change
 Рис. 7. Схема сил, действующих на буровой инструмент при внедрении его в породу по винтовой траектории: P – осевое усилие; $P_{уд}$ – направленная ударная нагрузка; P_y – сопротивление породы внедрению; P_z – сопротивление породы резанию; α – возможная область изменения ударной нагрузки

drilling by the fact that in the power stroke, the drill bit penetrates rocks with rotation at a small angle. The illustration is given by the curves of the penetration depth h of the drilling tool edge and the impact load angle α during the time t in Fig. 8. During movement of the drilling tool toward the rock mass and in the tool penetration in rock during t_p , the tool edge moves at a strictly defined angle α relative to the drill bit axis and makes helical movements in the time t_i .



This force impact generates additional shear and tensile stresses. Since the ultimate shearing and tension strength of rocks is significantly less than the compression strength of rocks, we can expect that such force impact produced by the drilling tool on rock mass forms more large-size shears, and, therefore, the efficiency of shearing and the rate of drilling will increase. Upon completion of the power stroke, the kinematics of the drilling tool movement is identical to the rotary percussive drilling kinematics, namely, the tool returns to its zero position in the time t_z and turns at an angle $\alpha = 15 - 20$ degrees in the time t_{turn} .

Fig. 8. Penetration depth h of drilling tool edge and impact load angle α in percussion rotary drilling along a helical path during t : t_p – percussion loading duration; t_{zr} – zero-point return of drill bit; t_{turn} – turning time; t_{il} – impact load time; t_i – idle rotation time of drilling tool

Рис. 8. Зависимость глубины внедрения h лезвий бурового инструмента от угла приложения ударной нагрузки α при ударно-поворотном бурении по винтовой траектории за время t : t_y – время ударно-поворотной нагрузки по винтовой траектории; t_b – время возврата инструмента в исходное положение; $t_{пов}$ – время, затрачиваемое на поворот инструмента; $t_{пн}$ – время движения бурового инструмента по винтовой траектории; $t_{хп}$ – время холостого поворота бурового инструмента

As a result of percussion rotary drilling with the bit penetration in rocks along a helical trajectory, in comparison with traditional rotary percussive drilling, the efficiency of shearing increases. The directional movement of the drill bit at an angle will form not only the forces necessary for penetration but also the forces required for shearing. Fig. 9 shows the conditional scheme of shearing in regular rotary percussive drilling (A) and in drilling by the proposed method (B). The diagram shows that in regular rotary percussive drilling (A), in section $ab-a'b'$, tool penetration and shearing towards the open plane are equal to the angle of rotation of the tool between impacts. In the case of drilling with penetration of the drill along a helical trajectory (B), additional shear stresses appear in the rock section $ab-a'b'$, which will increase the efficiency of shearing and, thus, ensure the process of rock destruction at the lowest energy consumption as compared with classical rotary percussive drilling.

Aimed to confirm this statement, the goal was set to perform mathematical and physical modeling of the drill bit edge penetration in rock mass, to obtain the dependences of the influence exerted by the angle of impact load application to the

surface of penetration on the efficiency of shearing and use the dependences to find an efficient pitch of the helical trajectory of the power stroke.

Mathematical modeling

The finite element method was used for the stress-strain analysis of rock under the drilling tool due to the action of a wedge simulating the drill bit edge. ANSYS Workbench was used as a software package for this study. As a result of modeling various force effects generated by the cutting wedge edge 1 mm wide on rock mass with Young's modulus $E = 1 \cdot 10^9$ Pa and Poisson's ratio $\mu = 0.3$, we obtained the stress-strain behavior patterns in rock in the zone under the edge (Fig. 10).

It is seen from Fig. 10a that the stress-strain fields ahead of the front edge of the wedge and under the cutting edge are approximately the same in simulated rotary drilling. In case of the thrust applied to the wedge (Fig. 10b), the wedge penetrates rock a little deeper. This can indirectly be judged by the patterns of the stress-strain fields in rock mass. When the thrust and impact load moment act on the wedge (Fig. 10c), the stress-strain fields arise in a larger volume as against the other cases, which is reflective of additional shear

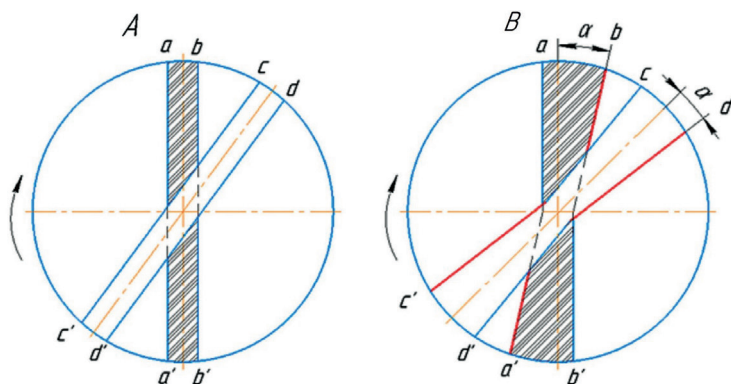


Fig. 9. Diagram of shearing in regular rotary percussive drilling (A) and in percussion rotary drilling along a helical trajectory (B)

Рис. 9. Схема образования сколов при ударно-поворотном бурении (A) и при ударно-поворотном бурении по винтовой траектории (B)

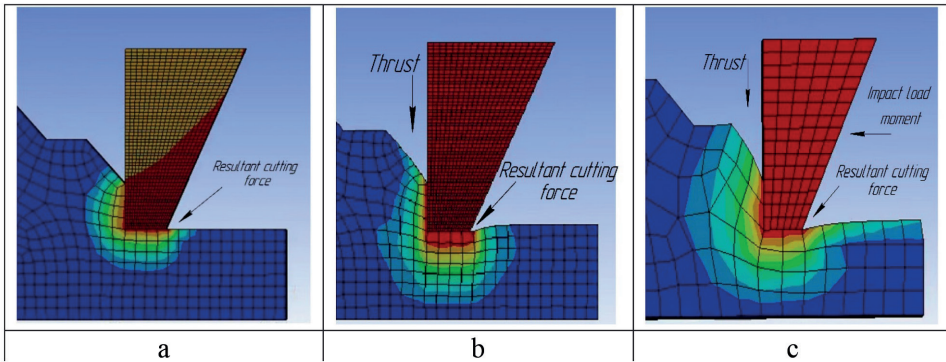


Fig. 10. Stress-strain behavior of rock mass in simulation of various drilling methods: a – rotary; b – rotary, with additional impulse thrust; c – rotary, with additional impulse thrust and load moment on wedge

Рис. 10. Схемы напряженно-деформированного состояния породного массива при имитации различных способов бурения: вращательного (а); вращательного с дополнительным импульсным воздействием осевой нагрузки (б); вращательного с дополнительными импульсными воздействиями осевой и моментной нагрузками на клин (в)

stresses in rock mass. This force impact will provide less energy-intensive fracture of rock due to the transfer of more energy in the form of strains to rock, which will allow a larger-size shear, will reduce friction between the wedge and rock, and will increase the shearing efficiency and, thus, the drilling rate [6 – 8].

The Abaqus/CAE finite element analysis software package was used for the mathematical modeling of the dependence between the shearing volume and the angle of the impact load application to the wedge. The Holmquist–Johnson–Cook fracture criterion was chosen as the fracture model. The mentioned criterion is

used to model mechanical damage of brittle materials (ceramics, concrete, etc.) in a range of strain rates. The model is applicable to plane strain, axially symmetric and three-dimensional solid elements, and can be used in both Lagrangian and Eulerian regions [9 – 11]. The modeling of the cutting edge penetration at a rate of 0.8 m/s to simulate the working edge of a drill cutter 0.5 mm wide, with a cut thickness of 2 mm, in the mode of the directional impact loading produces the qualitative pattern of large-size shearing in Fig. 11 [12 – 14].

It is seen in Fig. 11 that for different values of the load application angles rela-

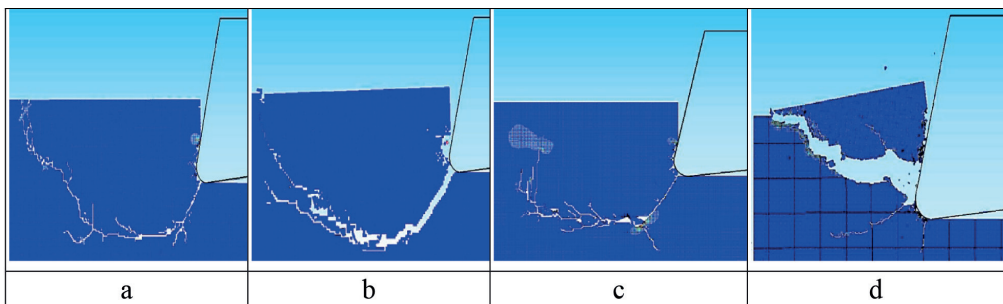


Fig. 11. Large-size shearing at different angles of impact load application to wedge: a – 30 deg; b – 45 deg; c – 55 deg; d – 90 deg

Рис. 11. Схемы формирования крупных сколов при различных значениях углов приложения ударной нагрузки к клину: 30 ° (а); 45 ° (б); 55 ° (в); 90 ° (г)

tive to the drill axis, different size shears are produced. At the impact load angle of 30 degrees (Fig. 11a) to the cutting plane, a shear 5 mm³ in volume is formed. With an increase in the angle of the impact load application to 45 degrees (Fig. 11b), the volume of sheared rock grows to 8 mm³. In case when the angle of the impact load is 55 and 90 degrees (Figs. 11c and 11d, respectively), the shearing volume decreases to 6 mm³ and 2 mm³ [15].

These results of mathematical modeling prove advisability of changing the direction of the impact load application to the drill bit edge to increase the shearing efficiency. Fig. 12 shows the curve of the shearing volume and the angle of the impact load application to the wedge simulating the working surface of a drill bit.

It is seen from Fig. 12 that the increase in the angle of the impact load application to the wedge to 45 degrees has a positive effect on the volume of rock shearing, while the higher angle has a negative influence. However, these results are rather qualitative in nature. Therefore, to obtain quantitative data and confirm the mathematical modeling data, physical modeling was carried out on a specially designed test bench for penetration of drill bits in rock mass at various impact load application angles and shock energy applied to the drill bit (Fig. 13). The test bench is made

as a gravity pendulum impact machine and consists of a table 1, base 2 and a headframe 3 with studding 4 to the base by 2. For kinematic connection between the headframe 3 and pulling 6, the machine is equipped with bearing units 5. An output element 7 is connected to the pulling 6 through the bearing units 5 and to the drill bit 8 by the bolt 10 set in a through hole. To change the impact energy on the rock surface 19, the weights 9 with mass m_1 , m_2 , m_3 are put on the shank of the drill bit 8. To raise the drill bit 8 with a mass m to the height $H = 1$ m, the test bench is equipped with winch 12, which is fixed through the hole on the drill bit shank 20 by the pulling rope 13, rollers 15 and a hook 17. To detach the hook 17 from the drill bit shank 20, the rail 18 is equipped with an eye bolt 21. To change the impact load application angle α , the inclined plate 11 is equipped with the rail 18 with through holes 16. Using the locking bolt 15, the plate is fixed at a preset angle α . The change step for α is 5 degrees.

After the drill bit impacts on rock mass, the shearing products were weighed on a scale with an accuracy of 0.01 g. To determine the dependence of the sheared rock volume on the angle of the impact load application, 10 shears were made on a rock sample at 9 values of the angles. The table presents the mass values of shearing

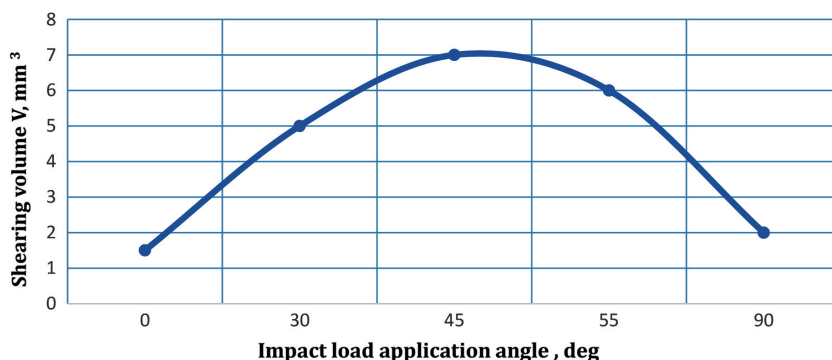


Fig. 12. Shearing volume versus impact load application angle

Рис. 12. График зависимости объема скола от угла приложения ударной нагрузки

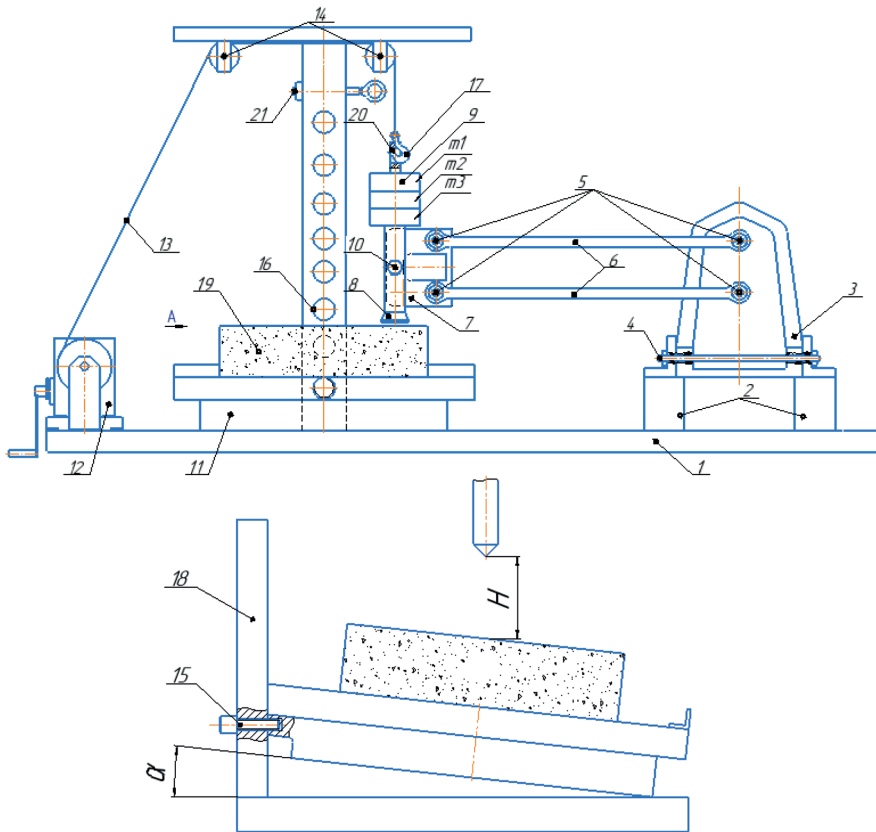


Fig. 13. Test bench, general view

Рис. 13. Общий вид стенда

products and the averaged values of this parameter depending on the impact load application angles.

Based on the physical modeling data on the shearing product volume versus the

application angle of impact load, a graph was plotted (Fig. 14). The graph shows that an increase in the impact load application angle increases the mass of sheared rock up to the highest value achieved at

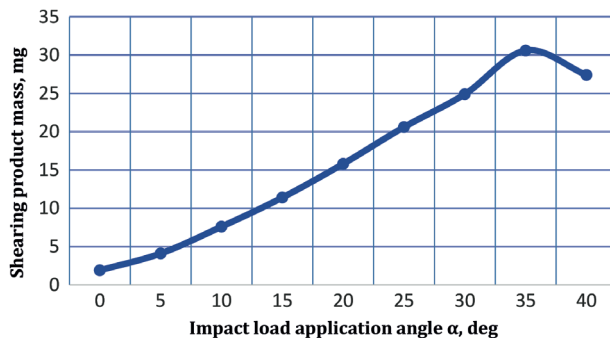


Fig. 14. Shearing product mass versus impact load application angle

Рис. 14. График зависимости массы продуктов скола от угла приложения ударной нагрузки

Dependence of shearing product mass on impact load application angle

Зависимость массы продуктов скола от величины угла приложения ударной нагрузки

| Rock | Plate tilt angle, deg | Shearing product mass, mg | | | | | | | | | | Averaged mass of shearing products, mg |
|--------|-----------------------|---------------------------|----|----|----|----|----|----|----|----|------|--|
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | |
| Gypsum | 0 | 1 | 1 | 3 | 2 | 4 | 1 | 1 | 3 | 1 | 2 | 1.9 |
| | 5 | 2 | 6 | 3 | 2 | 5 | 2 | 3 | 2 | 2 | 5 | 4.1 |
| | 10 | 7 | 11 | 7 | 9 | 8 | 9 | 10 | 7 | 11 | 6 | 7.6 |
| | 15 | 11 | 13 | 10 | 12 | 10 | 12 | 9 | 14 | 11 | 12 | 11.4 |
| | 20 | 12 | 13 | 16 | 15 | 17 | 16 | 15 | 14 | 18 | 17 | 15.8 |
| | 25 | 19 | 21 | 23 | 21 | 20 | 22 | 19 | 20 | 22 | 19 | 20.6 |
| | 30 | 24 | 23 | 24 | 26 | 22 | 27 | 26 | 25 | 27 | 24 | 24.9 |
| | 35 | 28 | 31 | 32 | 30 | 32 | 31 | 29 | 32 | 31 | 30 | 30.6 |
| 40 | 24 | 29 | 27 | 26 | 28 | 29 | 28 | 30 | 27 | 26 | 27.4 | |

the angle of 35 degrees. As against the test at the angle of 0 degrees, the mass of the shearing products at the impact load application angle of 35 degrees grows 15 times approximately.

The results obtained, to a first approximation, give reason to believe that bit drill penetration in rocks should follow not a linear but a helical path. In order to apply load impact to the drill bit edge at an angle of 30–40 degrees relative to the axis of the drill bit, the pitch of the helical path should be 4–6 diameters of a drill hole.

Conclusions

1. The percussion rotary drilling efficiency can be increased by changing the mode of drill bit penetration in rock, namely, by driving the drill bit not along the ax-

ial but along the helical path, and the pitch of the helical path should ensure deviation of the impact load vector of the bit edge from the hole axis by the value sufficient for the most effective shearing.

2. The mathematical and physical modeling of drill bit penetration in rock at various angles of impact load application exhibits significant effect of this parameter on the shearing efficiency.

3. The results obtained prove advisability of further research to optimize application angle and energy of the impact load depending on the physical and mechanical properties of rocks and to determine the influence of the drilling tool geometry on the drilling efficiency, which will certainly serve as the basis for improving drilling equipment.

СПИСОК ЛИТЕРАТУРЫ

1. Юнгмейстер Д. А., Уразбахтин Р. Ю., Мельников Д. А. Горные машины с модернизированными конструкциями ударных исполнительных органов / Технологическое оборудование для горной и нефтегазовой промышленности: сборник научных статей XV Международной научно-технической конференции. – 2017. – С. 124–128.

2. Сысоев Н. И., Гринько Д. А., Кожевников А. С. Повышение эффективности функционирования очистных и бурильных машин дискретным управлением их режимных параметров // Горное оборудование и электромеханика. – 2018. – № 3(137). – С. 37–42.

3. Хазанович Г. Ш. Актуальные направления научных исследований горнопроходческого оборудования // Горное оборудование и электромеханика. – 2018. – № 2(136). – С. 41–45.

4. Лукьянов В. Г., Крец В. Г. Горные машины и проведение горно-разведочных выработок: учебник для СПО. – М.: Изд-во «Юрайт», 2016. – 342 с.

5. Тургель Д. К. Горные машины и оборудование подземных разработок: Учебное пособие. — Екатеринбург: Изд-во УГГУ, 2007. — 302 с.

6. Сысоев Н. И., Буренков Н. Н., Чу Ким Хунг Обоснование структуры и выбор рациональных конструктивных параметров бурового резца, армированного алмазно-твердосплавными пластинами // Известия вузов. Северо-Кавказский регион. Технические науки. — 2016. — № 2. — С. 77–83.

7. Сысоев Н. И., Гринько Д. А., Гринько А. А. Исследование напряженно-деформированного состояния природного массива при импульсно-моментном воздействии на буровой инструмент / Технологическое оборудование для горной и нефтегазовой промышленности: сборник трудов XVI Международной научно-технической конференции «Чтения памяти В.Р. Кубачека», 12–13 апр. 2018 г. — Екатеринбург: УГГУ, 2018. — С. 283–287.

8. Сысоев Н. И., Чу Ким Хунг Определение максимально возможной скорости бурения шпуров численным моделированием // Горное оборудование и электромеханика. — 2016. — № 2. — С. 20–26.

9. Pryhorovska T. O., Chaplinskiy S. S., Kudriavtsev I. O. Finite element modelling of rock mass cutting by cutters for PDC drill bits // Petroleum Exploration and Development. 2015. Vol. 42. No 6. Pp. 888–892.

10. Yari N., Kapitaniak M., Vaziri V., Ma L., Wiercigroch M. Calibrated FEM modelling of rock cutting with PDC cutter // MATEC Web of Conferences. 2018. Vol. 148. Article 16006. DOI: 10.1051/mateconf/201814816006.

11. Helmons R. L. J., Miedema S. A., van Rhee C. Modeling the effect of water depth on rock cutting processes with the use of discrete element method // Terra et Aqua. 2016. Vol. 142. Pp. 17–24.

12. Che D., Zhu W.-L., Ehmann K. F. Chipping and crushing mechanisms in orthogonal rock cutting // International Journal of Mechanical Sciences. 2016. Vol. 119. Pp. 224–236.

13. Cheng Z., Sheng M., Li G. Cracks imaging in linear cutting tests with a PDC cutter: Characteristics and development sequence of cracks in the rock // Journal of Petroleum Science and Engineering. 2019. Vol. 179, Pp. 1151–1158. DOI: 10.1016/j.petrol.2019.04.053.

14. Протосеня А. Г., Иовлев Г. А. Прогноз пространственного напряженно-деформированного состояния физически нелинейного грунтового массива в призабойной зоне тоннеля // Горный информационно-аналитический бюллетень. — 2020. — № 5. — С. 128–139. DOI: 10.25018/0236-1493-2020-5-0-128-139.

15. Сысоев Н. И., Гринько Д. А., Гринько А. А. Математическое моделирование влияния угла приложения ударной нагрузки при бурении горной породы на эффективность сколообразования // Вестник Научного центра по безопасности работ в угольной промышленности. — 2019. — № 2. — С. 70–75. **PLoS**

REFERENCES

1. Jungmeister D. A., Urazbakhtin R. Yu., Melnikov D. A. Mining machines with modernized designs of percussion tools. *Tekhnologicheskoe oborudovanie dlya gornoj i neftegazovoy promyshlennosti: sbornik nauchnykh statej XV Mezhdunarodnoy nauchno-tekhnicheskoy konferentsii* [Technological Equipment for the Mining and Oil and Gas Industry: XV International Scientific–Technical Conference Proceedings], 2017, pp. 124–128. [In Russ].

2. Sysoev N. I., Grinko D. A., Kozhevnikov A. S. Increasing efficiency of functioning of cutter–loader and drilling machines by discrete management of their regime parameters. *Mining Equipment and Electromechanics*. 2018, no 3(137), pp. 37–42. [In Russ].

3. Khazanovich G. Sh. Current trends in scientific research of mining equipment. *Mining Equipment and Electromechanics*. 2018, no 2(136), pp. 41–45. [In Russ].

4. Lukyanov V. G., Krets V. G. *Gornye mashiny i provedenie gorno-razvedochnykh vyrobotok* [Mining machines and prospecting holes: Textbook], Moscow, Izd-vo «Yurayt», 2016, 342 p.

5. Turgel D. K. *Gornye mashiny i oborudovanie podzemnykh razrabotok* [Underground mining machines and equipment: Educational aid], Yekaterinburg: Izd-vo UGGU, 2007, 302 p.

6. Sysoev N.I., Burenkov N.N., Chu Kim Hung. Structure justification and rational design parameters for drill bit reinforced with diamond carbide inserts. *Izvestiya vuzov. Severo-Kavkazskiy region. Tekhnicheskie nauki*. 2016, no 2, pp. 77 – 83. [In Russ].

7. Sysoev N.I., Grinko D.A., Grinko A.A. Stress-strain analysis of rock mass in drilling by tool under impact momentum. *Tekhnologicheskoe oborudovanie dlya gornoy i neftegazovoy promyshlennosti: sbornik trudov XVI Mezhdunarodnoy nauchno-tekhnicheskoy konferentsii «Chteniya pamyati V.R. Kubacheka»* [Technological equipment for the mining and oil and gas industry: XVI International Scientific-Technical Conference Proceedings – Lectures in Memory of V.R. Kubachek], Yekaterinburg: Izd-vo UGGU, 2018, pp. 283 – 287. [In Russ].

8. Sysoev N.I., Chu Kim Hung. Determination of the maximum possible drilling speed of holes by numerical simulation. *Mining Equipment and Electromechanics*. 2016, no 2, pp. 20 – 26. [In Russ].

9. Pryhorovska T.O., Chaplinskiy S.S., Kudriavtsev I.O. Finite element modelling of rock mass cutting by cutters for PDC drill bits. *Petroleum Exploration and Development*. 2015. Vol. 42. No 6. Pp. 888 – 892.

10. Yari N., Kapitaniak M., Vaziri V., Ma L., Wiercigroch M. Calibrated FEM modelling of rock cutting with PDC cutter. *MATEC Web of Conferences*. 2018. Vol. 148. Article 16006. DOI: 10.1051/mateconf/201814816006.

11. Helmons R. L. J., Miedema S.A., van Rhee C. Modeling the effect of water depth on rock cutting processes with the use of discrete element method. *Terra et Aqua*. 2016. Vol. 142. Pp. 17 – 24.

12. Che D., Zhu W.-L., Ehmann K. F. Chipping and crushing mechanisms in orthogonal rock cutting. *International Journal of Mechanical Sciences*. 2016. Vol. 119. Pp. 224 – 236.

13. Cheng Z., Sheng M., Li G. Cracks imaging in linear cutting tests with a PDC cutter: Characteristics and development sequence of cracks in the rock. *Journal of Petroleum Science and Engineering*. 2019. Vol. 179, Pp. 1151 – 1158. DOI: 10.1016/j.petrol.2019.04.053.

14. Protosenya A. G., Iovlev G. A. Prediction of spatial stress-strain behavior of physically nonlinear soil mass in tunnel face area. *MIAB. Mining Inf. Anal. Bull.* 2020, no 5, pp. 128 – 139. [In Russ]. DOI: 10.25018/0236-1493-2020-5-0-128-139.

15. Sysoev N.I., Grinko D.A., Grinko A.A. Mathematical modeling of influence exerted by impact load angle on shearing efficiency in drilling. *Vestnik nauchnogo tsentra po bezopasnosti rabot v ugol'noy promyshlennosti*. 2019, no 2, pp. 70 – 75. [In Russ].

ИНФОРМАЦИЯ ОБ АВТОРАХ

Гринько Антон Александрович¹ – аспирант, e-mail: nextdingo@mail.ru,

Сысоев Николай Иванович¹ – д-р техн. наук, профессор,
e-mail: sysoevngmo@gmail.com,

Гринько Дмитрий Александрович¹ – канд. техн. наук,
доцент, e-mail: dingo17@mail.ru,

¹ Южно-Российский государственный политехнический университет (НПИ) им. М.И. Платова.

Для контактов: Гринько А.А., e-mail: nextdingo@mail.ru.

INFORMATION ABOUT THE AUTHORS

A.A. Grinko¹, Graduate Student, e-mail: nextdingo@mail.ru,

N.I. Sysoev¹, Dr. Sci. (Eng.), Professor, e-mail: sysoevngmo@gmail.com,

D.A. Grinko¹, Cand. Sci. (Eng.), Assistant Professor, e-mail: dingo17@mail.ru,

¹ M.I. Platov South-Russian State Polytechnic University (NPI),

346428, Novocheerkassk, Russia.

Corresponding author: A.A. Grinko, e-mail: nextdingo@mail.ru.

Получена редакцией 26.04.2020; получена после рецензии 17.06.2020; принята к печати 20.08.2020.

Received by the editors 26.04.2020; received after the review 17.06.2020; accepted for printing 20.08.2020.