UDC 539.538; 622.24.051.624

P. S. BESHENKOV[1]*, Technologist*
N. I. POLUSHIN[2]*, Associate Professor, Candidate of Engineering Sciences, Head of Superhard Materials Research Laboratory*
S. GKHORBANI[2]*, Lecturer, Candidate of Engineering Sciences, siamak.ghorbani@misis.ru*
E. N. SOROKIN[2]*, Senior Researcher*

[1]Engineering Ceramics Plant, Aprelevka, Russia
[2]National University of Science and Technology—MISIS, Moscow, Russia

STRESS DISTRIBUTION ANALYSIS OF PDC DRILL BITS BY COMPUTER MODELING*

Bits equipped with polycrystalline diamond compact (PDC) cutters are used in different purpose drilling in soft, medium-hard and, sometimes, hard rocks. The drill bit load, speed and torque, as well as density and cutting angles of cutters influence the PDC drilling efficiency. Improvement of drilling performance is one of the top priority economic goals. Production drilling is faced with a lot of technical problems to be solved to ensure high quality and efficiency of drilling. One of the predominant objectives of drilling is to select the best drill bit and to determine optimal drilling parameters as they directly govern the hole drilling cycle, the drill bit life, as well as the time and cost of drilling. Stresses in the body and cutting elements affect the behavior and productivity of PDC drill bits, as well as the running characteristics and failure-tolerance of cutters. High stresses can induce separation of the diamond compact top from the tungsten carbide substrate and initiate microcracks in the diamond layer. The microcracks grow and promote critical degradation of cutting tools in the course of drilling. The specified problems are commonly solved using software programs such as Solidworks Simulation, that make it possible to perform strength analysis, to obtain stress distribution patterns and to account for the influence exerted by angles of attack of PDC cutters on their stress state. This study is focused on stress distribution in cutting elements of PDC drill bits. The forces applied to the cutting elements of PDC drill bits are determined in the normal conditions and under critical impact loading. The effect exerted by the angles of attack of PDC cutters on the stress distribution and magnitude in drill bits is revealed.

Key words: *drill bit, drilling, PDC cutter, diamond and tungsten carbide plate, mechanical stress, cutting angle, computer modeling*
DOI: *10.17580/em.2017.02.06*

Introduction

Drill bits with Polycrystalline Diamond Compact (PDC) cutters known as PDC drill bits are used for different purpose drilling in soft, medium hard and, sometimes, hard rocks [1, 2]. A PDC drill bit comprises a polycrystalline diamond top layer and a tungsten carbide substrate for damping impact loads [3, 4]. PDC drilling performance is governed by: the load on a drill bit, the bit speed, the torque related with the load, the drill bit density and cutting angle [5]. A key aspect of drilling efficiency in oil and gas production is high abrasive resistance of PDC cutters [6, 7]. Furthermore, PDC tools have high resistance to cracking. This is of particular importance in hard rock drilling and in dynamically unstable drilling processes [8, 9].

Production drilling is faced with many technical problems to be solved to ensure drilling quality and efficiency. Selection of the best drill bit and determination of the optimal drilling parameters are the prime objectives that govern directly the drilling cycle, the drill bit service life and the drilling time and cost [10]. Enhancement of drilling efficiency is one of the critical economic goals.

Stresses in the body and cutters of PDC drill bits affect their behavior and performance. Stresses have influence on running characteristics and fault-tolerance of PDC cutting elements [11]. High stresses in the tools can result in separation of the diamond compact layer from the tungsten carbide substrate and induce microcracks in the diamond top. Microcracks can grow in the course of drilling and lead to critical degradation of the cutting tools [6, 12].

The mechanism of rock destruction at different angles of cutting is analyzed using the finite element modeling method in [13]. It is found that upper-set PDC cutters are subject to higher stresses than the center-set PDC cutters, and fail first. For another thing, it is revealed that stresses in PDC cutters are proportional to the cutting angels, and the increase in the angle of cutting results in the higher rate breaking of cutters during drilling. The upper side PDC cutters fail under higher force applied to them. The research results [14–16] show that PDC cutters fail under shearing stresses rather than under compressive or tensile stresses; the interrelation between stresses at critical points and PDC cutter inclination is analyzed. It is also found that damage of PDC cutters can be prevented by the correct selection of inclination, diameter and number of cutting elements.

Despite the innovative technologies introduced, such events as critical stresses yet occur during drilling. This appreciably affects drilling cost and time. Optimization of the performance and layout of a drilling tool can be based on testing new-designed prototype models as in [17]. Computer-aided modeling of drill bits also helps improve drill bit performance. The analysis of the obtained results enables optimizing the drill bit design and assessing the developments by

---

*This study has been carried out in the framework of the Federal Targeted Program on R&D in Priority Areas of Advancement in the Science and Technology of Russia for 2014–2020 in accordance with the Project on Development of the Technology for Production of Nanostructure Materials for Load-Bearing Substrates with High Impact Strength under the Grant Agreement No. 14.579.21.0093 dated July 27, 2015 (Unique Agreement Identifier FMEFI57915X0093) within the Integrated Project on the Technology of High-Efficient Horizontal and Inclined Drilling Bits for Oil and Gas Industry.

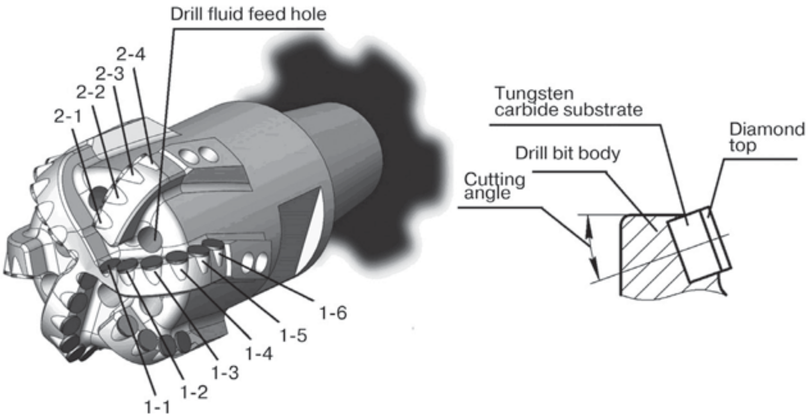

Fig. 1. SolidWorks 3D model of drill bit and ordering of cutters on drill blades

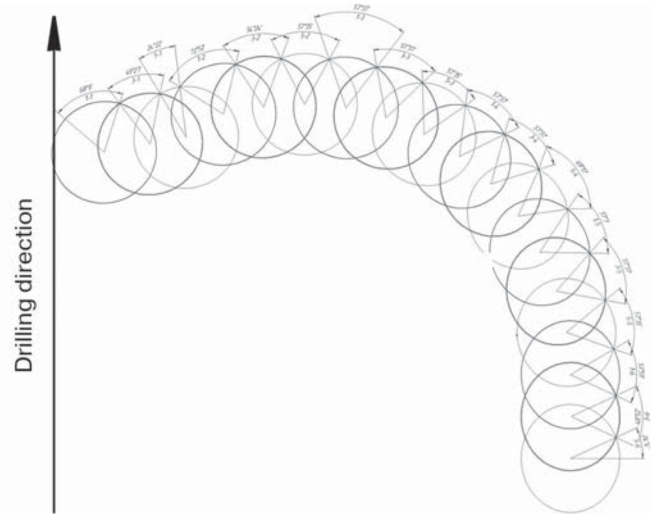

Fig. 2. Distribution of forces on drill bit cutters

recomputations without manufacture and full-scale testing of prototypes, which essentially accelerates the processes of drill bit design refinement.

Computer modeling widely uses such software products as Solidworks Simulation to analyze strength characteristics, plot stress distribution patterns and influence exerted by PDC angles of cutting on stresses applied to the drill bits.

Mathematical model

A drill bit consists of a steel body and a set of cutters composed of a tungsten carbide substrate and a diamond compact top. **Fig. 1** shows the 3D model of a drill bit.

Ordering of cutting elements:

Leading digit is a number of a blade;

Second digit is a number of a cutter on the blade starting from the center to the periphery.

For each cutting element, the cutting sector is shown with regard to the overlap with the neighbor cutters. It should be taken into account that operation of all cutters on an odd blade, starting from the third cutter, is coupled with the operation of cutters on an even blade, i.e., blade are coupled as 1–4, 3–6 and 5–2. The ordering of the cutters on a blade is given for blades 1 and 2 in Fig. 1.

The initial force applied to the drill bits is assumed the load of 98 kN after averaging the drilling log data courtesy of Gazprom Neft company. This load is taken by 30 drill bit cutters as illustrated by the scheme in **Fig. 2**.

The force exerted on each drill bit cutter is calculated as the composition of the normal and torque forces. The normal force on a cutter is proportional to the volume of cut rock and is determined using the formula (1):

$$Fi = \left(P / V_{tot}\right) V_i \,, \tag{1}$$

where F_i — normal force on an i-th cutter, N; P — total force on a drill bit, V; V_{tot} — total cut rock volume, m^3; V_i — rock volume cut by the i-th cutter, m^3.

The torque force is given by the formula (2):

$$F_{mi} = \frac{M_i}{l_i}, \tag{2}$$

where F_{mi} — torque force on an i-th cutter, N; M_i — moment on each cutter, N/m; l_i — distance between the drill bit axis and the i-th cutter, m.

The total force P_i, on each cutter in the normal conditions of drilling is determined from the formula below:

$$Pi = \sqrt{\left(F_i\right)^2 + \left(F_{mi}\right)^2} \,, \tag{3}$$

The calculation results on the forces on drill bits are presented in **Table 1**.

The total force P_i on a cutting element in the fault-duty mode of drilling is given by:

$$P_i = \sqrt{\left(F_{tot} + F_{mi}\right)^2 + F_i^2} \,, \tag{4}$$

where F_{mi} — torque force on an i-th cutter, N; F_i — normal force on the i-th cutter, N; F_{im} — impact load, N, found from the formula (5) [18]:

Table 1. Calculated forces on cutting elements of drill bits

Cutting element no.	Force, kN	Cutting element no.	Force, kN	Cutting element no.	Force, kN
1–1	6823	3-1	9677	5-1	6670
1–2	23971	3-2	24980	5-2	18776
1–3	18511	3-3	20740	5-3	22084
1–4	22391	3-4	21483	5-4	19307
1–5	15957	3-5	11652	5-5	7377
1–6	2919	3-6	118	5-6	47
2–1	22084	4-1	24826	6-1	20740
2–2	19307	4-2	22391	6-2	21483
2–3	7377	4-3	15957	6-3	11652
2–4	47	4-4	2920	6-4	118
Total load on cutting elements, N					422390

Table 2. Calculated forces on cutting elements of drill bits under critical impact loading

Cutting element no.	Force, kN	Cutting element no.	Force, kN	Cutting element no.	Force, kN
1–1	75446	3–1	78235	5–1	75296
1–2	92265	3–2	93257	5–2	87156
1–3	86895	3–3	89085	5–3	90408
1–4	90710	3–4	89816	5–4	87677
1–5	84388	3–5	80168	5–5	75987
1–6	71640	3–6	68914	5–6	68845
2–1	90408	4–1	93106	6–1	89085
2–2	87677	4–2	90710	6–2	89816
2–3	75987	4–3	84388	6–3	80170
2–4	68845	4–4	71639	6–4	68914
Total critical load on cutting elements, N					2598323

$$F_{tot} = 160gm\ , \qquad (5)$$

where g — acceleration of gravity, m/s^2;

M — weight of a drill bit, kg.

Table 2 gives the calculation data on the forces on cutting elements under critical impact loading.

Computer modeling and results

The strength analysis of a drill bit was carried out in the static mode with SolidWorks Simulation. After drawing a drill bit, its 3D model is constructed as in Fig. 1.

The program SolidWorks displays stress distribution maps of the strength analysis. **Fig. 3** shows the map of equivalent stresses in the normal conditions of drilling. According to the analysis, the second, third and forth cutters on blades 1, 3 and 5 are subjected to the highest loads. On blades 2, 4 and 5, the most loaded are cutters nos. 1, 2 and 3.

Table 3 describes the properties of materials the drill bits are made of.

The research [19] proves that the inefficient operation of PDC drill bits is connected with the ill arrangement of PDC cutters in terms of the angles of attack. In this connection, the present authors have carried out computer modeling of stress distribution in a drill bit in static conditions at different cutting angles: 0°, 5°, 10°, 15°, 25° and 30°. By the computation data, the least stress is exerted on a drill bit with the cutting angle of 30°. With the decrease in the angle of attach (cutting), stresses grow. The drill bit with the cutting angle of 5° is exposed to the highest stress. The modeling of the drill bit operation under critical impact loading conditions yields the same results.

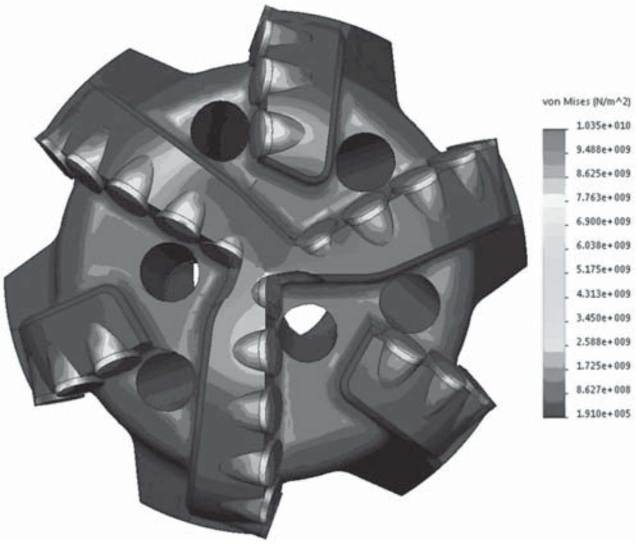

Fig. 3. Equivalent stress distribution in drill bit operation under static conditions

Conclusions

Thus, the numerical modeling of stress state of a drill bit has produced:

— distribution of loads on drill bit cutting elements in the normal conditions of drilling and under critical impact loading;

— distribution of stresses on PDC cutting elements depending on the cutting angles (angles of attack).

From the analysis of the resultant pattern of stress distribution in cutting elements of drill bits, the cutters subjected to the highest loads are identified, and the drill bit design is optimized with respect to the angles of attack of the cutters.

Referances

1. Neskoromnykh V. V., Borisov K. I. Analytical investigation of the process of cutting and shearing of rock by the bit with PDC cutters. *Izvestiya Tomskogo politekhnicheskogo universiteta*. 2013. Vol. 323, No. 1. pp. 191–195.
2. Bugakov V. I., Laptev A. I. Manufacturing technology of drill bits under high pressure and temperature with the application of new diamond materials. *Izvestiya vuzov. Chernaya metallurgiya*. 2017. Vol. 60, No. 1. pp. 36–42.
3. Maslov A. L., Markova I. Yu., Zakharova E. S., Polushin N. I., Laptev A. I. Tribological tests of wear-resistant coatings used in the production of drill bits of horizontal and inclined drilling. *IOP Conf. Series: Journal of Physics: Conf. Series, 2017*. No. 857. pp. 1–5.
4. Polushin N. I., Ovchinnikova M. S., Sorokin M. N. Decrease of the content of metals in diamond layer of PCD polycrystals by chemical and electrochemical etching. *Izvestiya VUZov "Poroshkovaya metallurgiya i funktsionalnye pokrytiya"*. 2017. No. 2. pp. 31–38.

Table 3. Properties of drill bit and cutter materials for the stress analysis

Material	Density, kg/m^3	Tensile strength, GPa	Compressive strength, GPa	Young's modulus, GPa	Poisson's ratio
Tungsten carbide	14100	1.9 (in bending)	3.9	560	0.23
Diamond top	4120	1.26	7.6	776	0.07
Steel 40	7850	0.57	0.5 ($\sigma_{0,2}$)	200	0.28

5. Tian J., Chuanhong F., Yang L., Yang Z., Pang X., You L., Zhu Y., Liu G. The Wear Analysis Model of Drill Bit Cutting Element with Torsion Vibration. *Advances in Mechanical Engineering.* 2014. Vol. 7, No. 1. pp. 1–9.
6. Kanyanta V., Ozbayraktar S., Maweja K. Effect of manufacturing parameters on polycrystalline diamond compact cutting tool stress-state. *International Journal of Refractory Metals and Hard Materials.* 2014. No. 45. pp. 147–152.
7. Kuftyrev R. Yu., Polushin N. I., Kotelnikova O. S., Laptev A. I., Sorokin M. N. Wear resistance of PCD composites used to complete PDC drill bits. *Izvestiya vuzov. Chernaya metallurgiya*. 2017. No. 9. pp. 52–61.
8. Belnap D., Griffo A. Homogeneous and structured PCD/WC-Co materials for drilling. *Diamond and Related Materials*. 2004. No. 13. pp. 1914–1922.
9. Borisov K. I. Dynamics of cutters operation during the rock failure by the cutting and shearing instruments PDC. *Izvestiya Tomskogo politekhnicheskogo universiteta.* 2010. Vol. 318, No. 1. pp. 161–164.
10. Jianhong F., Kexiong S., Zhi Z., Dezhi Z., Fei L., Xin X., Xin Z. Stress analysis on drilling string vibration in gas drilling. *Energy Procedia*. 2012. No. 16. pp. 1264–1268
11. Paggett J. W., Drake E. F., Krawitz A. D., Winholtz R. A., Griffin N. D. Residual stress and stress gradients in polycrystalline diamond compacts. *International Journal of Refractory Metals and Hard Materials.* 2002. No. 20. pp. 187–194.
12. Yahiaoui M., Gerbaud L., Paris J.-Y., Denape J., Dourfaye A. A study on PDC drill bits quality. *Wear*. 2013. No. 298–299. pp. 32–41.
13. Zhu. H., Liu Q., Deng J. et al. Rock-breaking mechanism of rotary-percussive drilling. *Journal of Basic Science and Engineering*. 2012. No. 4. pp. 622–31.
14. Huang Z., Tan L., Jin X. et al. Mechanical analysis and incline design of percussion-rotary drill bit side teeth. *Equipment for Geophysical Prospecting*. 2007. No. 2. pp. 87–91.
15. Fu Y. The approach of improving the shatter-resistant capability of ball gear brazing head alloy teeth. *Rock Drill Machine Pneumatic Tools*. 1988. No. 3. pp. 38–43.
16. Tan Z., Lai H. The failure analysis of ball tooth bit side tooth. *Rock Drill Machine Pneumatic Tools*. 1990. No. 3. pp. 17–24.
17. Polushin N. I., Laptev A. I., Baragunov E. M. Influence of the structure of diamond drill bits' matrices on their abrasion resistance. Part 2. Research of wear resistance of diamond drill bits. *Tsvetnye Metally*. 2013. No. 2. pp. 72–75.
18. Ishbaev G. G., Vagapov S. Yu. Modern elements. *Zhurnal Bureniya i Nefti*. 2012. No. 6–7. pp. 44–46.
19. Gusman A. M. Ways of creation of efficient bits PDC for hard rock drilling. *Vestnik Assotsiatsii burovykh podryadchikov*. 2000. No. 1. pp. 28–32. EM

UDC 622.232.72

A. V. STEBNEV[1], *Chief Mechanic*
S. G. MUKHORTIKOV[1], *Vice-Chief Mechanic, Candidate of Engineering Sciences*
D. A. ZADKOV[2], *Associate Professor, Candidate of Engineering Sciences, dzadkov@yandex.ru*
V. V. GABOV[2], *Professor, Doctor of Engineering Sciences*

[1]*SUEK-Kuzbass, Leninsk-Kuznetsky, Russia*
[2]*Saint-Petersburg Mining University, Saint-Petersburg, Russia*

ANALYSIS OF OPERATION OF POWERED LONGWALL SYSTEMS IN MINES OF SUEK-KUZBASS

The geological conditions and mining technology used in mines of SUEK-Kuzbass company are described. Mining machines and equipment included in the powered longwall mining systems are examined. The main criteria of any longwall system efficiency are output per face, productivity, life time and failure-free operation of mining machines. This study is focused on the downtime in longwalls and on the most significant factors connected with the mining equipment failures and complicated ground conditions including unstable roof, frequent roof rock falls, rockburst-hazard, high gas content, etc. It is found that 15% of downtime is taken by the mine safety measures to be implemented, and 56% of idling is due to the other production and technical reasons. Such events that intersection of faults, high methane release, unstable and very unstable roof with doming and rock falls, high water inflows and kicks, increased strata pressure, false floor and intensive roof rock fracturing entail long-term stoppage of work of the powered longwall systems, many non-productive operations and appreciable production loss. The productivity of the powered longwall systems in mines of SUEK-Kuzbass is analyzed with a view to estimating their operational stability in rational modes in fully mechanized longwalls. To this effect, the curves of output per face for 12 months and for a few years have been analyzed. An emphasis should be laid on the high nonuniformity in the values of output per face, i.e. there is considerable deviation of actual performance of the powered longwall systems from their specifications. The plotted density functions for output per face per mines within SUEK-Kuzbass are closely spaced, which points at the similar history of the processes. Despite the modern high-tech equipment, longwall mining has an erratic performance and capabilities of the powered longwall systems are used inefficiently. In order to refine the factors that condition the nonuniformity of output per face, it is planned to study the actual feed velocities of shearers and the real-time operation of a powered longwall system.

Key words: *coal, bed, underground mining, longwall system, shearer, powered roof support, conveyor, downtime, operating mode, stability, output per face, productivity*
DOI: *10.17580/em.2017.02.07*

Introduction

SUEK-Kuzbass is an affiliate to the Siberian Coal Energy Company — SUEK. SUEK-Kuzbass comprises mines situated in the territory of the Kemerovo Region: Kirov, Ruban, Yalevsky, Komsomolets, Polysaevskaya, Talda-Zapad-1 and Talda-Zapad-2.

Table 1 gives a brief description of the mines within SUEK-Kuzbass as of 2016. Coal mining is carried out at a depth of 180–470 m. The thickness of coal beds varies from 1.7 to 4.5 m, dip angles range as 0–20°; gas flow rate in longwalls is from 5 to 122 m^3/min, and the length of longwalls is 186 to 300 m.

Some of SUEK-Kuzbass mines operate closely spaced coal beds under the impact of