EQUIPMENT AND MATERIALS

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**STRESS DISTRIBUTION ANALYSIS OF PDC DRILL BITS BY COMPUTER MODELING**

**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 angles, 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

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**Key words:** drill bit, drilling, PDC cutter, diamond and tungsten carbide plate, mechanical stress, cutting angle, computer modeling

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**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.**

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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):

\[ F_i = \left( \frac{P}{V_{tot}} \right) V_i, \]

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):

\[ F_{mi} = \frac{M_i}{l_i}, \]

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:

\[ P_i = \sqrt{\left( F_i \right)^2 + \left( F_{mi} \right)^2}, \]

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:

\[ P_i = \sqrt{\left( F_{tot} + F_m \right)^2 + F_i^2}, \]

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

<table>
<thead>
<tr>
<th>Cutting element no.</th>
<th>Force, kN</th>
<th>Cutting element no.</th>
<th>Force, kN</th>
<th>Cutting element no.</th>
<th>Force, kN</th>
</tr>
</thead>
<tbody>
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<td>6670</td>
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<tr>
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<td>20740</td>
<td>5–3</td>
<td>22084</td>
</tr>
<tr>
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<td>3–4</td>
<td>21483</td>
<td>5–4</td>
<td>19307</td>
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<tr>
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<td>11652</td>
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</tr>
<tr>
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<td>3–6</td>
<td>118</td>
<td>5–6</td>
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<td>4–4</td>
<td>2920</td>
<td>6–4</td>
<td>118</td>
</tr>
</tbody>
</table>

Total load on cutting elements, N 422390
Cutter of PDC drill bits

The cutting element of drill bit is subjected to the highest loads and under critical impact loading. The Program SolidWorks gives 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.

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

<table>
<thead>
<tr>
<th>Cutting element no.</th>
<th>Force, kN</th>
<th>Cutting element no.</th>
<th>Force, kN</th>
<th>Cutting element no.</th>
<th>Force, kN</th>
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<td>71639</td>
<td>6–4</td>
<td>68914</td>
</tr>
</tbody>
</table>

Total critical load on cutting elements, N 2598323

\[ F_{\text{tot}} = 160gm, \]  

where \( g \) — acceleration of gravity, m/s²; \( M \) — 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 attack (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.

Table 3. Properties of material for the stress analysis

<table>
<thead>
<tr>
<th>Material</th>
<th>Density, kg/m³</th>
<th>Tensile strength, GPa</th>
<th>Compressive strength, GPa</th>
<th>Young’s modulus, GPa</th>
<th>Poisson’s ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tungsten carbide</td>
<td>14100</td>
<td>1.9 (in bending)</td>
<td>3.9</td>
<td>560</td>
<td>0.23</td>
</tr>
<tr>
<td>Diamond top</td>
<td>4126</td>
<td>1.26</td>
<td>7.6</td>
<td>776</td>
<td>0.07</td>
</tr>
<tr>
<td>Steel 40</td>
<td>7850</td>
<td>0.57</td>
<td>0.5 (( \sigma_{e,2} ))</td>
<td>200</td>
<td>0.28</td>
</tr>
</tbody>
</table>

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.

References


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

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, Yaleyvsky, Komso- molets, Polyasevskaya, 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 m³/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 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, powered 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 shearsers 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

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