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Method of Drilling Process Control and Experimental Studies of Resistance Forces During PDC Cutter Drilling

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Abstract

An effective control system, grounded in theoretical principles and empirical validation, is essential for optimizing the drilling process while minimizing time and material costs. The advent of advanced rock-cutting tools, particularly polycrystalline diamond (PDC) cutters, has highlighted the need for developing methods and criteria for optimal drilling process control, especially for applications involving medium-hard rocks. This paper analyzes the forces at play between the rock-cutting elements, the rock face, and the drilling mud, identifying key influencing factors and providing formulas to determine rock failure parameters. Empirical validation of the theoretical concepts was conducted using data from experimental drilling of marble with 76.2 mm diameter PDC cutters. The experiments employed a full factorial design to develop mathematical models and graphical representations of the influencing factors. The method proposed for controlling the drilling process focuses on finding the optimal balance between tool rotation frequency, axial weight, and penetration per rotation. This approach enables the identification of the rock failure mode at the bottom of the well through indirect indicators, facilitating the selection of drilling parameters that maximize mechanical drilling speed while ensuring efficient operation of the rock-cutting tool. A schematic is included, outlining potential bit operation modes and methods for recognizing them based on the ratios of penetration per rotation and the rotation frequency of the cutting tool.

Keywords: Diamond drilling; full factorial experiment; drilling process control; drilling tool development; PDC cutters; drilling modes.

Introduction

The use of PDC cutters as rock-cutting elements in the production of crowns and bits represents a significant advancement in rock-cutting tool technology. These tools are capable of achieving high drilling speeds across a wide range of rock hardness, while also offering considerable durability. However, the dynamics of force interactions between the rock-cutting elements, the face rock, and the drilling mud remains an area that has not been thoroughly explored. The resistance forces encountered when using PDC cutter bits have a substantial impact on the fracture process and overall drilling efficiency, particularly affecting the wear of the cutters themselves. Research indicates that the most pronounced cutter wear occurs at a point approximately 0.8 times the bit radius, highlighting the crucial role of resistance forces in cutter performance. This force is influenced by the linear speed of the cutters, which increases from the center to the periphery of the cutter in accordance with the equation \(2\pi \omega r\), where \(\omega\) is the bit's rotation frequency. K.I. Borisov's research specifically examines how the movement speed of the cutter during the cutting and chipping of rocks affects the rock failure process.

Furthermore, a dependence derived from Borisov's work shows the relationship between the resistance coefficient to rock failure and the axial weight on the cutter, based on experimental studies. It reveals that the resistance coefficient increases during the elastic deformation stage of the rock and decreases when stresses lead to active bulk failure and irreversible plastic deformation, such as crack formation. It is important to note that this analysis does not consider the resistance from the surrounding environment, including the drilling mud and the rubble of already broken rock that remains at the well bottom. Research Methodology

This study examines theoretical propositions that account for the resistance posed by both the rock that has already been broken before reaching the cutter and the resistance from the surrounding environment, including drilling mud, when using PDC cutter bits. To better understand the forces and reactions involved, we refer to the diagram (Fig. 1).

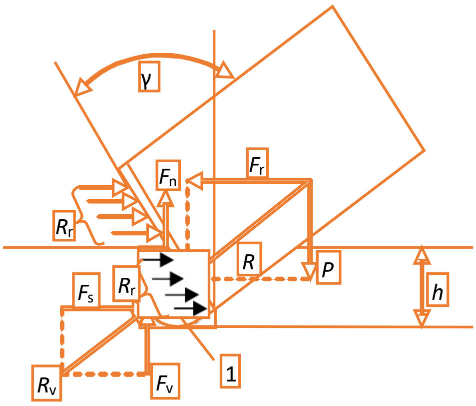

Fig.1. Diagram for analyzing the process of cutting – chipping rock with a PDC cutter 1 – rock compression core

Discussion:

To empirically assess the calculated resistance values, we examine data from experimental drilling of marble using 76.2 mm diameter PDC cutters. The drilling was conducted following a full factorial experimental design with two influencing factors: axial weight and rotation frequency. This approach yielded models that capture the drilling process from different perspectives, considering both the penetration rate and tool life, as well as the amount of penetration per rotation—an essential parameter for managing the drilling operation.

$$v_m = 5{,}74 + 4{,}43\, P_{os} + 3{,}14\, \omega + 2{,}3\, P_{os}\, \omega, \quad (9)$$
$$h_{Rev} = 0{,}83 + 0{,}64\, P_{os} - 0{,}08\, \omega - 0{,}06\, P_{os}\, \omega, \quad (10)$$
$$N = 10{,}04 + 8{,}48\, P_{os} + 3{,}76\, \omega + 2{,}63\, P_{os}\, \omega, \quad (11)$$
$$N/v_m = 1{,}9 + 0{,}37\, P_{os} - 0{,}24\, \omega - 0{,}307\, P_{os}\, \omega. \quad (12)$$

The analysis of energy intensity, as depicted in model, identifies the optimal drilling modes, indicating that a penetration rate of 1.3-1.4 mm/rev will be effective and will yield nearly the highest mechanical drilling speed under the experimental conditions.

Conversely, during bulk failure, the pattern reverses: the maximum penetration (h_1) is associated with the lowest rotation frequency ($50 min^{-1}$), and the minimum penetration (h_3) aligns with the highest rotation frequency ($200\ min^{-1}$).Figure 5 displays graphs illustrating the relationship between penetration per rotation and rotation frequency at an axial weight of 330 daN for the fatigue-surface failure mode, and 600, 750, and 800 daN for the bulk failure mode. The data indicate that during fatigue-surface failure, penetration per rotation increases as the rotation frequency of the drilling tool rises. In contrast, during bulk failure, penetration per rotation decreases with increasing rotation frequency, suggesting that resistance from the rock and the surrounding environment increases as the linear cutting-chipping speed escalates. Moreover, the rate at which penetration per rotation decreases intensifies with higher axial weights, leading to greater cutter penetration into the rock.

The rate of decrease in penetration per rotation, expressed in terms of angle β allows for the calculation of the resistance coefficient as the tangent of this angle.

This is due to the fact that in the fatigue-surface failure mode, the maximum penetration per rotation occurs at the highest rotation frequency, a trend supported by numerous experimental findings.

Results

The practical application of these findings can be utilized in diagnosing the rock failure mode while controlling the drilling process using interactive systems, such as bottom-hole telemetry systems or computer support systems like APS. Figure 6 illustrates a program for managing drilling mode parameters. For instance, at stage I, the rotation frequency increases from ω1 to ω2 while maintaining a constant axial weight of 500 daN. During this process, the penetration per rotation decreases due to the increased resistance forces from the fractured rock and surrounding environment, which leads to forces that diminish the axial weight. Consequently, the mechanical speed is determined by the product $v_m = h_1\omega_2$. Since the depth decreases from (h_0) to (h_1), any increase in (v_m) will be minimal or nonexistent. To address this issue, we can move on to stage II, which involves increasing the axial weight to 600 daN while reducing the rotation frequency to ω_{12}. This adjustment will yield a higher mechanical drilling speed compared to stage I, where the rotation frequency was lower. In this scenario, adjustments to the rotation frequency—from ω_2, to ω_3, and ω_4—will necessitate increases in axial weight, moving from 600 to 700, and then to 800 daN. This will allow for a gradual increase in mechanical drilling speed as the rotation frequency rises.

To find the optimal relationship between the chosen rotation frequency and axial weight in an interactive drilling process control mode, empirical models like and their graphical representations can be utilized These empirical models generated in interactive mode and their interpretations enable quick adjustments to drilling parameters, facilitating efficient bit development. In ideal conditions, the optimal mode for bit operation is bulk rock failure. However, during extended drilling intervals where varying rock drillability occurs, bit wear can lead to changes in the volume of drilling mud generated, the effectiveness of face cleaning, and the supply of cleaning agents. These shifts may cause a transition from the advantageous bulk failure mode to the less effective fatigue-surface failure mode. For example, as a bit wears down or as it transitions from soft to harder rock, the failure mode might shift to fatigue-surface. Insufficient flushing could result in face slamming, while excessive drilling mud supply might create hydraulic support for the bit's end, or overheating of the bit could lead to active thermomechanical failure. Interactive support for bit development, considering the established relationships between penetration per rotation at the drill's bottom and drilling parameters, facilitates timely and optimal adjustments to bit development conditions.

Conclusion:

By integrating theoretical principles with practical testing methods for controlling drilling bits with PDC cutters, and accounting for resistance forces, we can automate the drilling process. This is achieved through the proposed algorithm for optimizing process conditions based on three main criteria: rotation frequency, axial weight, and penetration per rotation, all while utilizing real-time data. Beyond managing the process within optimal parameter ranges, the interactive drilling control method allows for the recognition of well bottom conditions and the adjustment of settings to mitigate adverse drilling situations or to select optimal parameters for achieving specific penetration rates at the drill's bottom. The drilling control method described in this article is applicable for drilling wells for solid minerals and oil and gas up to a depth of approximately 1000-1500 m. Beyond this depth, the influence of destructive factors, such as increasing rock pressure, can significantly impact the management process. The extended length of the drill string and potential complexities in well profiles contribute to increased power losses due to friction and the development of oscillatory processes, negatively affecting the transfer of axial weight and rotation frequency from the wellhead to the bit.

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