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Weight on Bit Self-Adjusting Dual-Diameter Bit and Its Indoor Experiments Analysis

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Abstract

Improving rate of penetration (ROP) to achieve safer and more efficient drilling is a major demand in the field of oil-gas exploration and development, therefore oil companies and drilling contractors are constantly innovating the research and transformation of rock-breaking drill bits. In this paper, a weight on bit (WOB) self-adjusting dual-diameter PDC bit (WSDB), which includes a pilot bit, reaming section, a WOB regulating spring and a transmission structure, with reasonable WOB self-regulation and releasing borehole stress is proposed to improve ROP by increasing WOB per cutter, reducing rock breaking torque and improving stress state of the borehole.

The drilling experiments in natural limestone show that WOB and revolutions per minute (RPM) are still the main factors affecting the ROP. Compared with conventional PDC bit, the ROP of WSDB can be increased by up to 325% at most. The rock-breaking torque is lower than that of conventional PDC bit under the same condition, and the reduction range could reach up to 20%; the mechanical specific energy(MSE) of Bit B is smaller than that of Bit A under the same conditions, and the reduction range is between 10% and 62.5%.

This new WSDB has the advantages of higher ROP, smaller rock-breaking torque and lower MSE under suitable WOB and RPM, and application of this new bit is attempted to improve the rock-breaking efficiency and prolong the life of the bit by changing its structure and the way to break the rock.

Introduction

Improving rate of penetration (ROP) to achieve safer and more efficient drilling is a major demand in the field of oil-gas exploration and development, therefore oil companies and drilling contractors are constantly innovating the research and transformation of rock-breaking drill bits[1-11].

The increasing number of ultra-deep wells makes the length of the large diameter well section (⩾Φ215.9mm) longer to meet the requirements of the wellbore configuration. As is shown in the Fig.1, which is a typical well profile in Oil Field of Karamay located in the Northwest region of China. The well depth has exceeded 8000m, of which the Φ311.1mm section depth has exceeded 5500m and Φ215.9mm section has been more than 6500m. With the deepening of the large-size well section, the problem of slow ROP is becoming more and more prominent and it has seriously affected the drilling cycle and cost of the whole well, thus affecting the progress of exploration and development of the entire oil field. How to improve the ROP of the large-diameter hole in deep wells has become an important subject for further study.

The increase of the large-size section in deep wells makes the application effect of PDC bits in the oil exploration field relatively worse. The reason, on the one hand: low water power utilization in soft strata leads to the inadequate of excavating by high pressure jetting and cuttings migration, being more prone to logy drill column and balling up phenomena. On the other hand: the lesser weight on PDC tooth per unit area that results in insufficient mechanical rock-breaking energy in hard formations and layers of gravel. At the same time, the case more than 5000m using one bit in one roundtrip is not rare (commonly known as single-bit well), while depth of cut of the same PDC bit in different strata cannot change which leading to intense torque fluctuation and stick-slip phenomenon, which reduces the service life of the bit and the bottom hole assembly (BHA)[12-14]. In the meantime, the increase in the diameter of the hole leads to the increasing of rock-breaking volume. For example, the rock-breaking volume of the Φ444.5mm section is 4.24 times that of the Φ215.9mm section and Φ311mm is 2.08 times that of the Φ215.9mm hole

In this paper, a WSDB, which includes a pilot bit, reaming section, a WOB regulating spring and a transmission structure, with reasonable WOB self-regulation and releasing borehole stress is proposed to improve ROP by increasing WOB per cutter, reducing rock breaking torque and improving stress state of the borehole. At the same time, rock-breaking experiments were carried out to verify its feasibility.

Bit Structure

The WSDB(Fig.2) consists of a reaming bit, a WOB regulating spring, a transmission assembly and a pilot bit. The pilot bit and the transmission assembly are connected into one, which is installed in the axial hole of the reaming bit, and the pilot bit protrudes from the crown of the reaming bit. The WOB regulating spring is located between the top of the transmission assembly and the bottom of the reaming bit joint[15]. The WSDB has a simple working principle, structure, wide application range, and can be applied to various strata, of which the expected effect in multi-interbedded formation is better.

Weight on Bit Self-adjusting

Similar to the mechanism of DOC control self-adjusting , the WSDB can automatically detect the lithologic characteristics of the strata to be drilled, and automatically distributes the WOB between the pilot bit and the reaming bit according to the drillability of the formation to be drilled. The process of adaptive WOB distribution is shown in Fig.3 when drills in the harder stratum and the pilot bit of WSDB meets resistance, then the WOB will be mainly applied to the reaming bit (Fig.3a). With the increase of footage drilled, the upper spring is compressed and drives the pilot bit penetrating under the action of WOB, and at this point, the WOB will be mainly allocated on top of the pilot bit (Fig.3b). When the pilot bit drills a distance while the spring elongating, weight on the pilot bit will be insufficient, and the ROP of the pilot bit is reduced, then the WOB is applied to the reaming bit. The specific rock breaking energy can be greatly reduced due to the stress release of the pilot hole drilled. The pilot bit leads the drilling process again when the internal spring is compressed, thus realizing the alternating distribution of weight on between the pilot and the reaming bit and the alternating drilling process.

Self-adjusting DOC Control

As shown in Fig.4, we can assume that there are three different strata in the same well, the upper softer section will not cause stick-slip vibration, and the lower B and C formations will induce different levels of stick-slip vibration to the bits. Ideally, we want the ROP in A section not to be limited, at the same time stick-slip vibration in the formation B and C to be eliminated when the same bit used during the drilling process.

The DOC of fixed cutter PDC bit can be optimized to eliminate the stick-slip in a specific target section, but it fails to mitigate stick-slip while maximizing the ROP in diverse sections of the well. At the same time, DOC optimization of the bit requires stratigraphic data of offset well and iterative optimization, which brings great challenges to the PDC bit achieving optimal ROP when drilling in different well segments[16].

When drilling into the upper softer stratum A, the elastic element inside WSDB is in small deformation, which makes the pilot bit stick out more and maximizes the ROP. In B and C strata, the large contact stress makes the internal elastic element compress, leading to the pilot bit retracting, buffering the DOC surge caused by the formation mutation, and gradually offset the stick-slip vibration to avoid the failure of the drill bit.

The above adaptive DOC function will only be motivated in complex strata such as interbedded or gravel layers, and it will not be engaged in other normal steady-state drilling conditions. It is precise because the WSDB can dynamically adjust the DOC control characteristics of the whole bit while increasing the ROP, it can alleviate the stick-slip vibration caused by the rapid change of DOC.

Proof-of-Concept Laboratory Tests

Due to the theoretical feasibility, we set up an experimental device for automatic data collection and processing during rock breaking, which can monitor and record in real time for drilling footage, drilling time, RPM, the torque on bit (TOB), WOB fluctuation and acceleration. The conventional PDC bit (Referred to as Bit A) (Fig.5a) and the WSDB (Referred to as Bit B) (Fig.5b) were designed and machined with the same diameter, and the drilling experiments with different drilling parameters were carried out using natural limestone samples.

The actual borehole pattern drilled by WSDB is shown in Fig.6, and the borehole quality produced by the WSDB is very similar to that of the conventional PDC bit. Due to its special two-stage structure, the pilot section drills the smaller borehole (the less energy required to drill a small diameter borehole) and the reaming section then drills the stress-released stratigraphic area (lower mechanical specific energy required in the stress released area), which makes it more efficient and faster to drill the same size borehole compared to conventional PDC bits.

Rate of Penetration

As shown in Fig.7a/b/c: the ROP of Bit B under different RPM conditions is larger than that of Bit A generally, and only under 52RPM and smaller WOB (<10kN), the ROP of Bit A is larger than that of Bit B. Under the condition of specific RPM, the ROP difference between Bits A and B will largen with the increase of WOB, which indicates that Bit B has better efficiency under the condition of bigger WOB. ROP curve of Bit B with increasing WOB is similar to the exponential form change, and the ROP curve of Bit A is approximately proportional to WOB; Under experimental conditions at maximum WOB (22.5kN) and maximum RPM (221RPM), Bit A appears to have reached its ROP limit.

In order to quantitatively explain the speed-up effect of Bit B, taking Bit A as the reference, the amplitude of increased ROP can be calculated as follows(Fig.7d): Bit B has the largest amplitude of increased ROP at 52RPM&22.5kN, the minimum value obtained at 221RPM. The maximum value got under the experimental conditions can reach up to 325%.

Torque on Bit

The experiments show that the torque generated by Bit B in the process of rock breaking is relatively smaller under the condition of similar ROP compared with Bit A. Another experimental scheme is set up in order to verify the conclusion furtherly. A relatively softer red sandstone was selected as a sample and drilled by Bit A and B with the same ROP, RPM, and similar WOB, to measure the TOB while getting the following experimental results: (with part of the data as an example to illustrate)

The ROP of Bits A and B under 12.5kN and 52RPM is: 13.01m/h and 12.71m/h, the ROP difference between the two bits is less than 2.4%. The mean TOB is 403.53N·m and 319.59N·m respectively, and the mean TOB value of Bit B is 79.2% of Bit A (Fig.8).

When drilling into limestone, relatively smaller torque is required by Bit B for higher-efficiency rock-breaking, which could also be supported by different ROP, TOB growth amplitude when drilling under the same parameters (Fig.9). At 52RPM, the ROP growth rate can be up to about 330%, while the maximum increase rate of torque under the same conditions is only 67% (Fig.9a). The same thing happens at 103RPM, ROP growth rate ranges from 50% to 270%, while the rate of increment of torque is about -37%~70%. At 221RPM, the amplitude of ROP increases at around 12%~100%, while the variation range of torque is between -43%~22%. In summary, Bit B in the process of drilling in limestone, compared with Bit A, ROP increase is generally larger, and the corresponding increase in TOB is smaller or even decreasing the trend, indicating that Bit B has the characteristics of faster and more efficient drilling with low TOB, and further expands its scope of application.

Mechanical Specific Energy

In order to further evaluate and compare the difficulty level of the rock-breaking process by different drill bits, the concept of MSE is introduced and compared. MSE Model used in the paper is proposed by Teale as follows[17]:

$$MSE = \frac{WOB}{A_b} + \frac{120\pi \cdot N \cdot T}{A_b \cdot ROP} \tag{1}$$

where MSE=Mechanical Specific Energy, $\times 10^3$Mpa; WOB=Weight on Bit, kN; A_b=Sectional Area of the Bit, mm^2; N=Revolutions of Rotary Table Per Minute, r/min; T=Torque on Bit, kN.m; ROP=Rate of Penetration, m/h; D_b=Diameter of the Bit, mm.

The MSE curves of Bit A and Bit B under 103RPM and different WOB parameters, as well as the relative MSE curves, are given respectively in Fig. 10a/b. From Fig.10a, it can be found that the MSE of Bits A and B decreases significantly with the increase of WOB, and it tends to be a stable value. The minimum value of MSE should be equal to the unconfined compressive strength of the rock ideally. The MSE value of Bit B is generally lower than that of Bit A under 103RPM, and it can be found from Fig.10b that the MSE of Bit B decreases between 10% and 62.5% compared to Bit A under the same conditions, which indicates that Bit B require less energy to break the same rock than that of Bit A.

Conclusions

This paper introduced a two-stage cutting structural WOB self-adjusting PDC bit, comprising a pilot bit to drill a smaller pilot hole and simultaneously providing reamer part to ream the “stress relieved” portion of the formation, of which two simultaneous cutting actions can result in more efficient drilling performance. In the meanwhile, this new bit can also make full use of its own structural characteristics, especially the internal elastic element. On the one hand, the automatic distribution of weight on the pilot bit and the reaming bit during drilling is made according to the drillability grade of the formation. On the other hand, it can dynamically adapt its DOC control characteristics to a constantly changing drilling environment to mitigate stick-slip vibrations while delivering improved ROP.

Through the indoor comparison test, it is found that compared with the conventional PDC bit, the ROP of WSDB can be increased by up to 325% when drilling in limestone. The ROP curve of Bit B with increasing WOB is similar to the exponential form change, and the ROP curve of Bit A is approximately proportional to WOB.

The experiments show that the torque generated by Bit B in the process of rock breaking is relatively smaller under the condition of similar ROP compared with Bit A, which indicates that Bit B has the characteristics of faster and more efficient drilling with low TOB, and further expands its scope of application.

MSE theory is introduced to evaluate the mechanical energy required for breaking the rock by Bit A and B in the drilling process. The results show that the MSE of Bit B is smaller than that of Bit A under the same conditions, and the reduction range is between 10% and 62.5%.

The WOB Self-Adjusting Dual-diameter Bit technology demonstrated significant potential to reduce vibration-related failures, reduce TOB and increase drilling efficiency by its two-stage cutting structure, stress release effect, WOB self-distribution, and self-DOC control, thus reducing drilling costs This success paves the way for an expanded field testing program. The success of this kind of new bit is also expected to widen its range of applications in new energy fields such as geothermal resources and combustible ice, etc.

Acknowledgments

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Nomenclature

ROP = *Rate of penetration, m/h*
WOB =*Weight on bit, kN*
WSDB = *weight on bit self-adjusting dual-diameter PDC bit*
RPM = *Revolutions per minute, r/min*
PDC =*Polycrystalline diamond compact*
MSE = *Mechanical specific energy, MPa*
DOC = *Depth of cut*
BHA = *Bottom hole assembly*

TOB =*Torque on bit, kN.m*
A_b =*Sectional Aera of the Bit, mm*^{2}
N =*Revolutions of Rotary Table Per Minute, r/min*
D_b =*Diameter of the Bit, mm*

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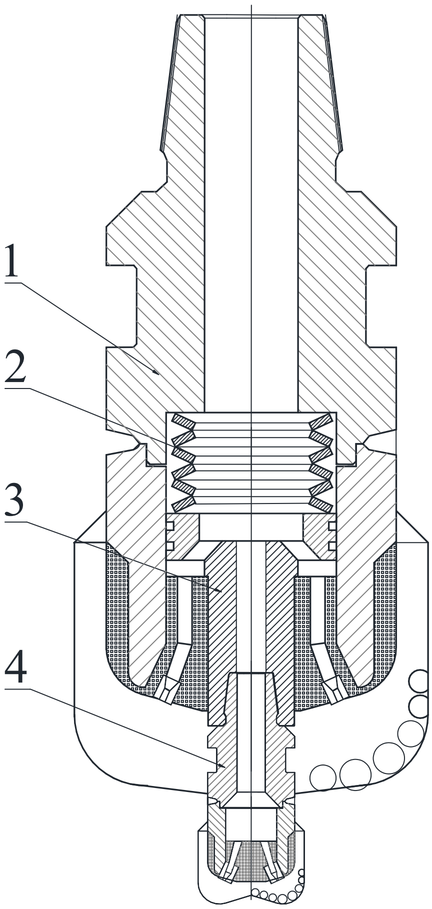
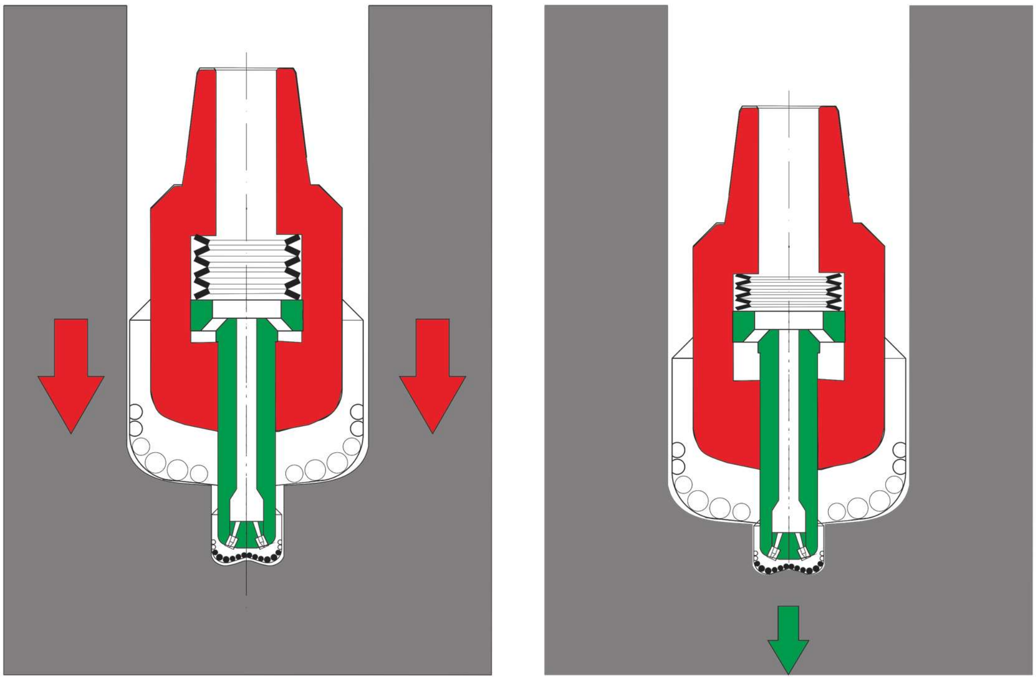
Fig.1 Typical Well Profile in Oil Field of Karamay



1-reaming bit，2-WOB regulating spring，3- transmission assembly，4-pilot bit

Fig.2 Basic Construction Plan of WSDB



(a) Weight on Reaming Bit，(b) Weight on Pilot Bit

Fig.3 Diagram of Weight Distribution Between the Pilot Bit and the Reaming Bit

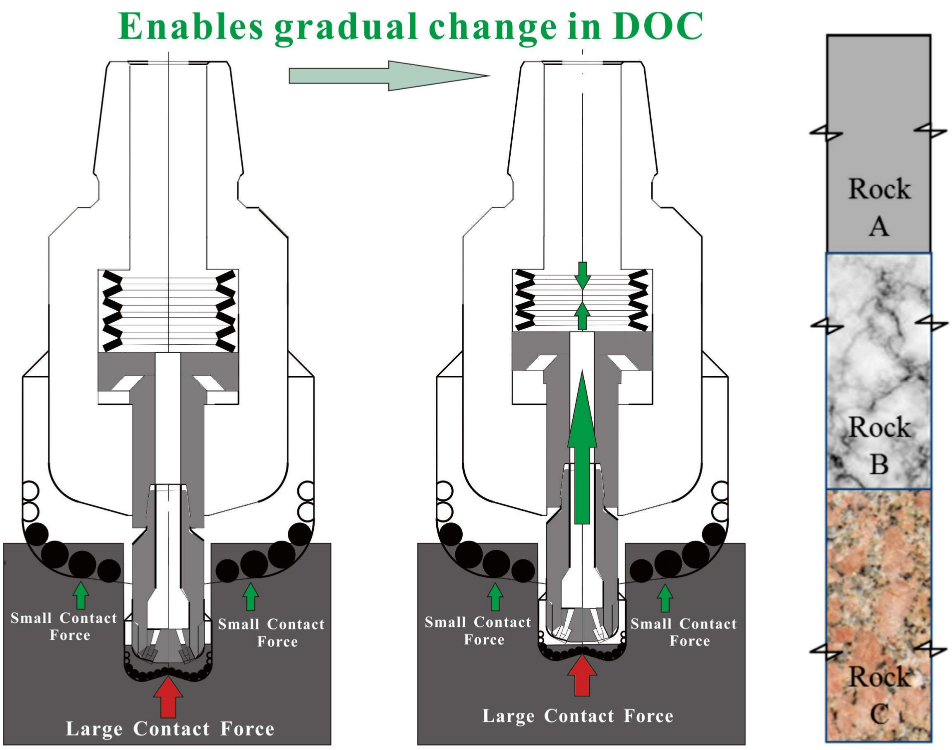


Fig.4 Schematic Diagram of Depth of Cut Control (DOCC)

(a) Conventional PDC Bit（Bit A）

(b) WOB Self-Adjusting PDC Bit（Bit B）

Fig.5 Two Kind of Experimental Bits

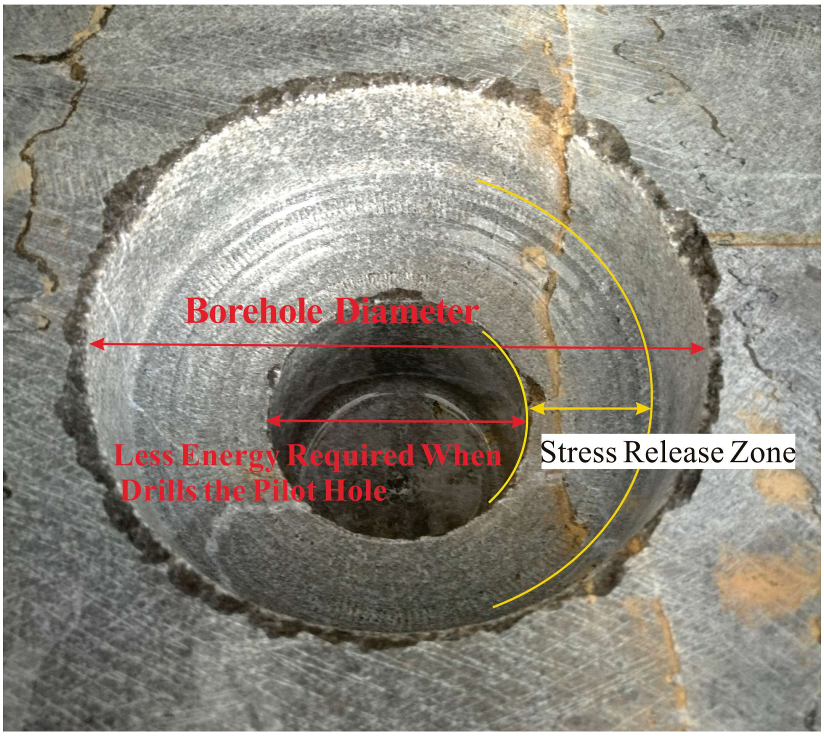
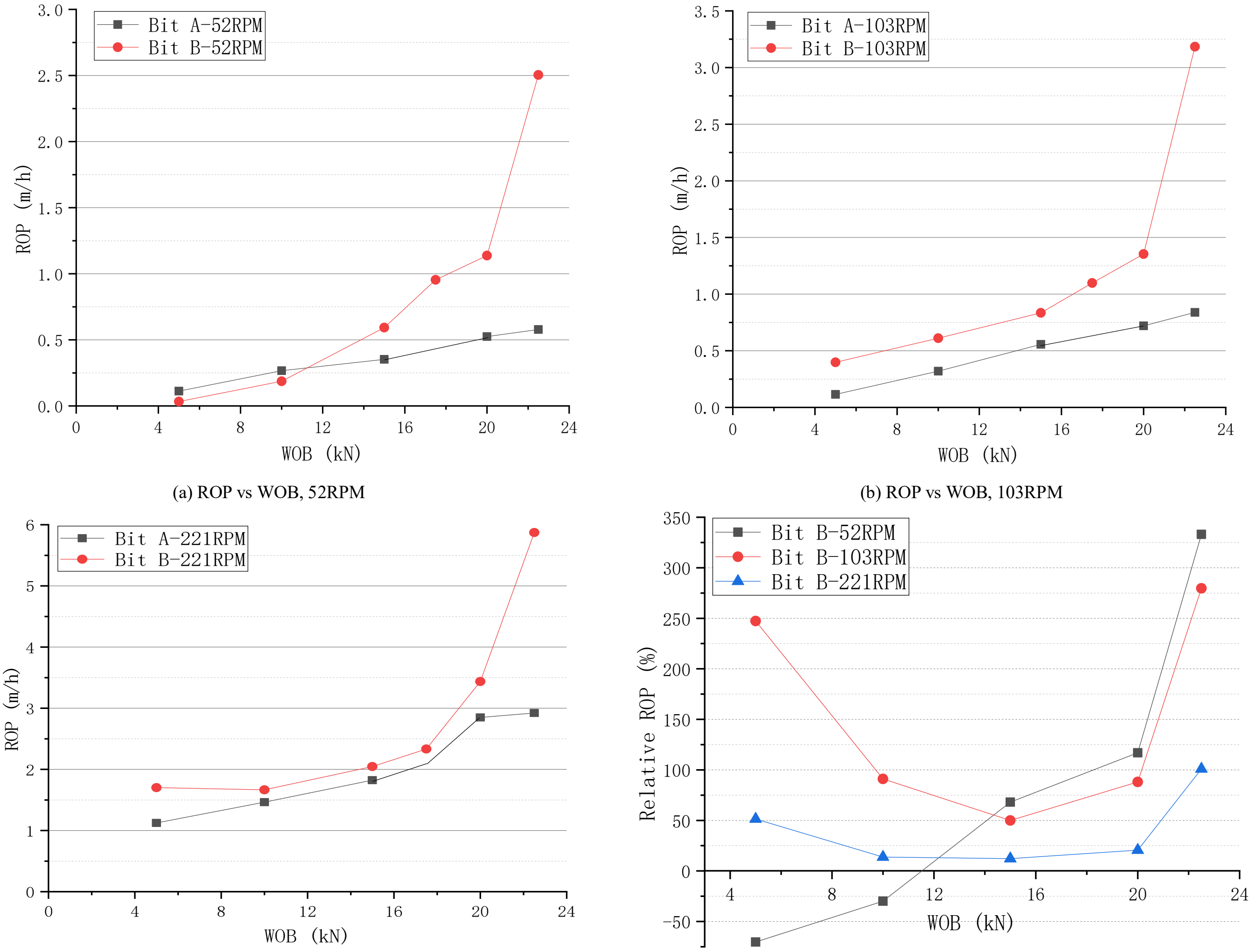


Fig.6 Actual hole drilled byWOB Self-Adjusting Dual-Diameter Bit



(a) ROP vs WOB, 52RPM

(b) ROP vs WOB, 103RPM

(c) ROP vs WOB, 221RPM

(d) Relative ROP vs WOB, 52/103/221RPM

Fig.7 ROP vs WOB

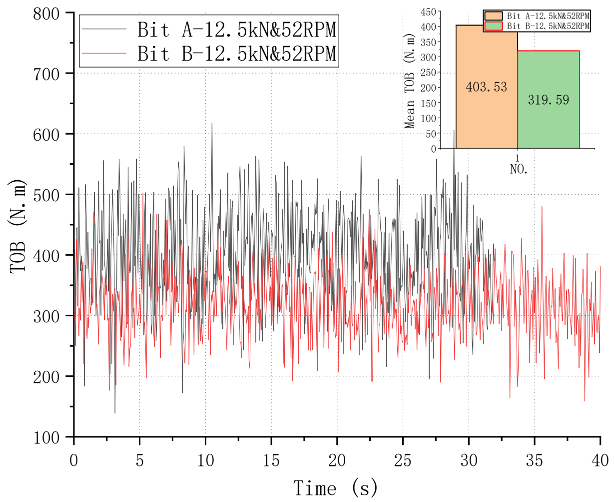
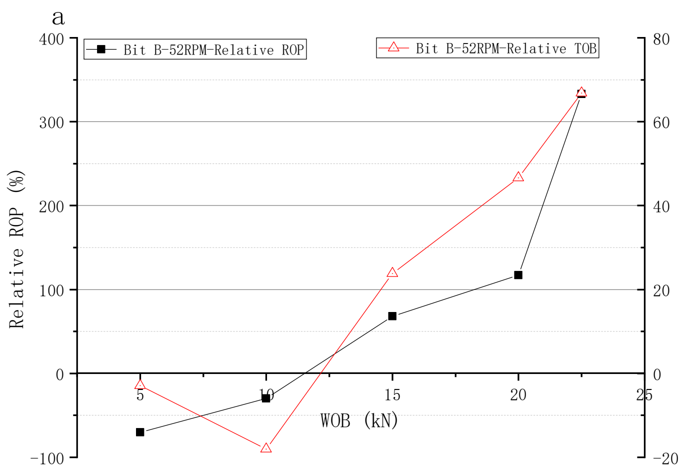
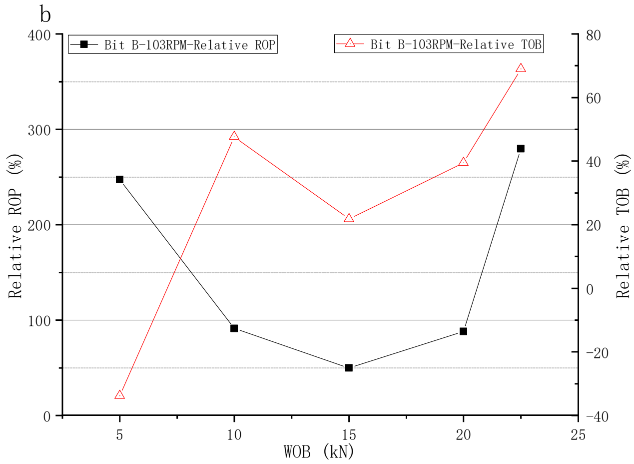


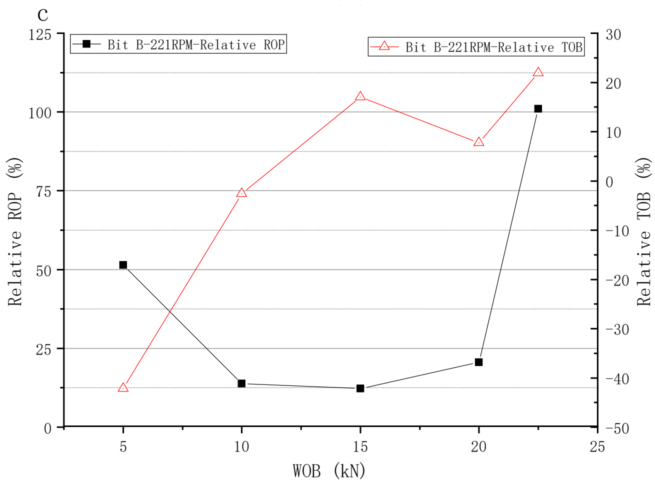
Fig.8 TOB Comparison Between Bit A and B in 12.5kN&52RPM



(a) Relative ROP& Relative TOB vs WOB, 52RPM

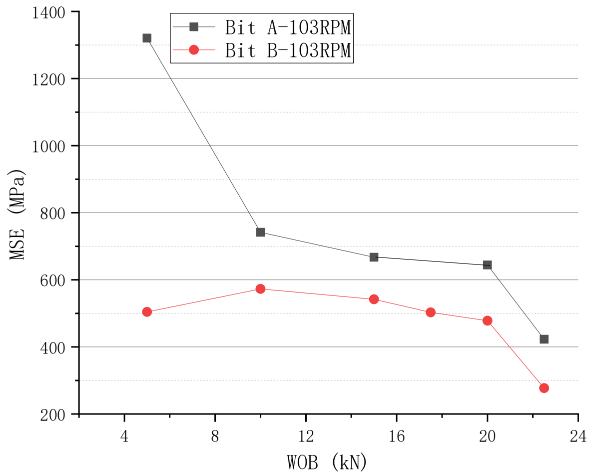


(b) Relative ROP& Relative TOB vs WOB, 103RPM

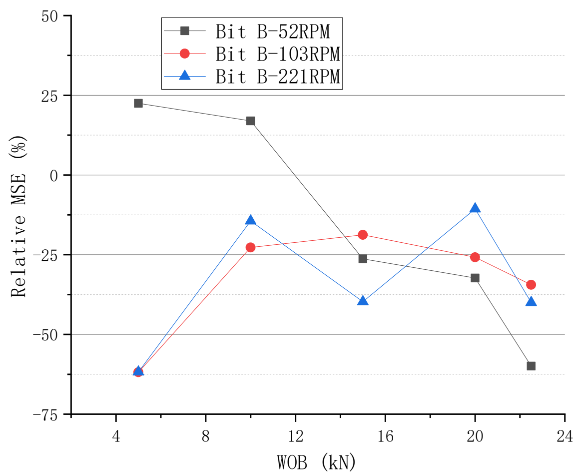


(c) Relative ROP& Relative TOB vs WOB, 221RPM

Fig.9 Relative ROP& Relative TOB vs WOB



(a) WOB vs MSE, 103RPM



(b) WOB vs Relative MSE

Fig.10 MSE& Relative MSE vs WOB