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Experimental Device Design and Load Test of PDC Single Cutter Scraping Considering Cyclotron Motion

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Abstract: The rotary motion of the bit caused by the lateral force imbalance of the bit leads to premature failure of the bit, mainly because the side of the cutter makes contact with the rock and participates in breaking rock. The rotating motion of the bit causes the bit to form an irregular spiral bottom hole.A lot of research and experiments have been done to eliminate the cyclotron phenomenon. However, whether it is conventional PDC cutter or special-shaped PDC cutter single cutter rock breaking experiment simulation or laboratory experiment, it is based on the way of replacing circular cutting of cutter with linear scraping, and almost does not consider the radial scraping motion of cutter under circular motion, which is still different from the actual working state of the bit. Therefore, in order to further understand the rock breaking characteristics of the cutter under irregular or circular motion, it is necessary to carry out a single rock breaking study considering the combined circumferential and radial scraping motion.

Keywords: PDC cutter, Rock crushing mechanics, Load.

1. Introduction

Polycrystalline Diamond Compact (PDC) bit was introduced in the 1970s because of its high rock breaking efficiency, high drilling rate, high penetration rate, long life, high reliability, relatively simple production process, flexibility of bit structure design, and short manufacturing cycle. The advantages of high economic benefits, thus in the world oil, natural gas drilling field has been more and more widely used, its demand increases year by year, and the performance of the drill is also increasingly high requirements. In order to improve the performance and range of use, since the 1980s, a lot of manpower and material resources have been invested in the research and development of drill bits at home and abroad, and certain achievements have been made. The drill has improved its performance and its ability to withstand hard formations and interbeddings significantly better than earlier products.

Karasawa and Li et al. used PDC cutters to carry out scraping tests on granite, limestone and shale at different angles to study the influence of cutting Angle on cutting load and torque [1,2].

He Renqing et al. used ANSYS software to study three kinds of traditional PDC cutters of different specifications under different dip angles and confining pressure. The stress nemogram reflected the shear rock breaking mechanism of traditional PDC teeth, and the larger the dip Angle, the more difficult the shear rock breaking. The greater the confining pressure, the stronger the rock plasticity, and the greater the cutting force required for rock breaking [3].

Jiang Xin et al. carried out impact tests on traditional PDC cutters on different rock samples, and the results showed that the tangential and axial impact forces PDC cutters suffered showed obvious linear relationships with cutting area, rock pressing strength and cutting speed, and thus established the impact load prediction model of traditional PDC cutters [4].

Li Hai used ABAQUS software to study the law of the influence of parameters such as confining pressure and front dip Angle on the rock cracking efficiency of traditional PDC under torsional impact [5].

The PDC bit has several blades, each of which is inlaid with inherent PDC cutters. In an ideal state, the axis of rotation of the bit and the shaft axis coincide, so that a series of concentric ring fracture marks are formed at the bottom of the hole during the process of PDC rotary drilling, as shown in Figure 1. PDC cutters are the basic units that interact with rocks directly to break rocks and form boreholes. Therefore, studying the rock breaking load of a single cutter of PDC bit is the premise of studying the rock breaking mechanism and failure reasons of the whole bit. For the rock breaking process of a single PDC cutter, whether it is physical experiment or numerical simulation, the current methods are mostly to simplify the circular scraping motion of PDC cutters into a straight scraping motion.

Figure 1. New compound bit structure and compound mode of cone and fixed wing

However, the movement of the bit at the bottom of the hole is not an ideal circular movement. Influenced by the bit structure, formation factors, well depth structure, drilling depth, etc., the axis of the bit rotation does not coincide with the axis of the hole, but there will be a certain deviation between the two axes. In this way, the size of the drilled hole will be increased, and the enlarged hole will further increase the deviation between the two axes. The resulting roundabout motion of the bit is shown in Figure 2. As shown in Figure 3, the bottom hole topography generated by bit rotation is a curved polygonal petal shape. From the causes of rotation and the bottom hole topography, it can be seen that the PDC cutters on the bit not only rotate around the bit axis, but also move in the radial direction of the wellbore.

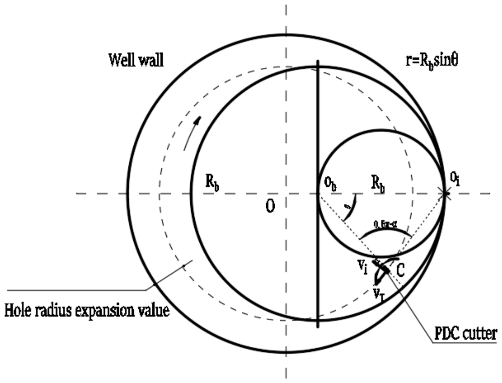


Figure 2. Principle of drill rotatory movement

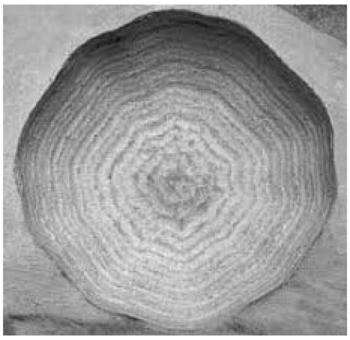


Figure 3. The circular motion generated at the bottom of the well

Therefore, in this paper, on the basis of replacing circular scraping with linear scraping of PDC cutters, the rock breaking mode of PDC cutters with circumferential rotation and radial movement is replaced by the synthesis of two mutually perpendicular linear motion directions, namely, one of the linear motion directions replaces the circular motion of PDC cutters. Radial motion of PDC cutters along the wellbore is replaced by linear reciprocating motion in another direction, as shown in Figure.2.

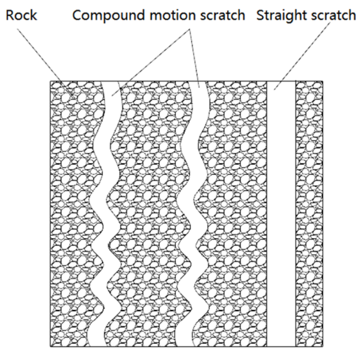


Figure 4. Straight cut and compound cut marks

In view of the PDC cutter motion mode generated by the above bit rotation principle, the schematic diagram of the PDC cutter scraping experimental device in this experiment is shown in Figure 5. The experimental facility is a retrofitted shaper from the Drill Bit Laboratory of Southwest Petroleum University. The equipment has the advantages of more constant cutting force, smooth, small impact force, linear motion speed is stable and easy to adjust, suitable for the cutting cutters impact resistance is poor and as far as possible to avoid noise interference requirements. Compared with the planer, the main changes are in the two aspects of planer and table. The original planer is replaced by a tool bar. The top of the tool bar is similar to the planer joint, and a three-way force sensor is installed in the middle, and PDC cutters for experiment are installed under the sensor. The change of the table mainly lies in the fact that there is a rotating rock sample holding box on the planer working table (hereinafter referred to as the rotating table). The working principle of the experimental equipment is shown in the figure. The rock is fixed on the rock rotating table placed on the planer working table. The rock rotating table can realize the adjustment of the cross Angle. The linear motion of planer process is the scraping of cutting; When the cutter is backing off, it is necessary to lift the sensor in time to avoid damaging the scraped track and sensor when the cutter is backing off. When compound scraping is needed, the feed screw handle on the planer is moved forward and backward so that the table has a straight reciprocating motion perpendicular to the tool holder of the planer.

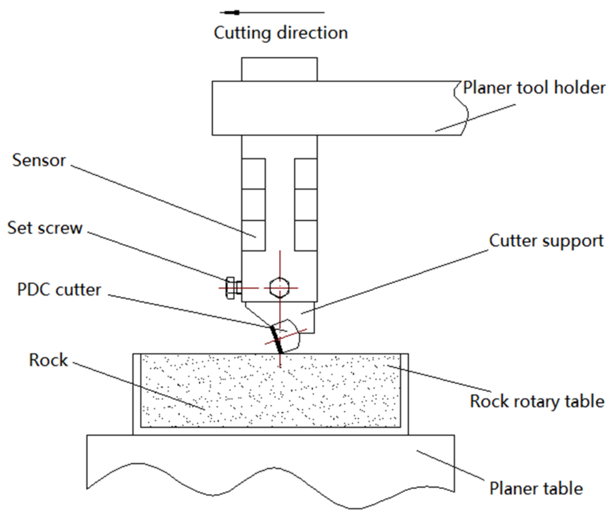


Figure 5. Principle of experimental apparatus

2. Experimental Content and Procedure

2.1. Experimental content

This experiment mainly conducted variable parameter experiments for different rock, cutter swing amplitude, swing frequency and cutting depth. Specific experimental parameters are shown in Table 1:

Table 1. Three Scheme comparing

1	Lithology(Rock)	S:Sandstone; L;limestone	Remarks
2	Cutter shape	16mm Cylindrical cutter	
3	Oscillation frequency	5 times, 4 times, 3 times (in the length of 300mm rock scraping and cutting PDC cutter round trip times)	
4	Cutter front angle	15°	
5	Depth of cutting	Sandstone: 1mm, 1.5mm, 2mm Limestone: 0.6mm, 1.2mm, 1.6mm	
6	Amplitude of oscillation	8mm, 6mm and 4mm	
7	Repeat straight line scraping after swinging	A straight cut is made on the oscillating scratch mark to the same depth as the scratch mark	
8	Sampling frequency	200Hz	
9	Straight cutting speed	0.1m/s	

2.2. Experimental procedure

Specific experimental steps are as follows:

①Connect sensors, dynamic signal acquisition instruments, computers, etc., to form a data acquisition system.

② Fix the rock in the rock holder.

③ Install PDC cutter.

④ Plane the rock.

⑤ Adjust the relative height between the unit experimental device and the rock, so that the PDC cutters in the specified depth of rock breaking work.

⑥ After checking everything is ready, the sensor and device on the planer are pulled up by rope first after data acquisition personnel start the command to the operator after data collection. When the planer returns to the minimum position, the rope is slowly lowered and the rock breaking device contacts and breaks the rock until the rope is pulled up when the planer finishes cutting the rock in a straight line. The rock breaking device is elevated away from the rock, at which time data collection is stopped and broken rock debris is collected. At this point, the first rock breaking process is completed. Each rock breaking process is repeated at least three times depending on the stability of the data.

⑦ Move the planer table around, so that the rock breaking device is in the next rock breaking position, repeat the above process, the difference is to shake the screw handle around, so that the rock moves around.

The experimental results are shown in Figure 6.

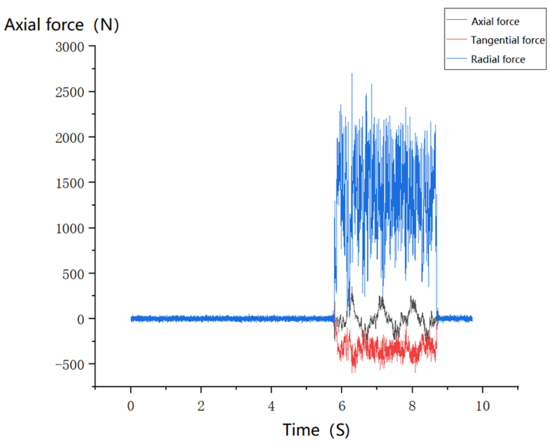


Figure 6. Experimental result

3. Experimental Result

3.1. Experimental equipment design and processing

PDC cutter breaking test device is composed of PDC cutter base, PDC cutter and sensor. The design is shown in Figure 7.

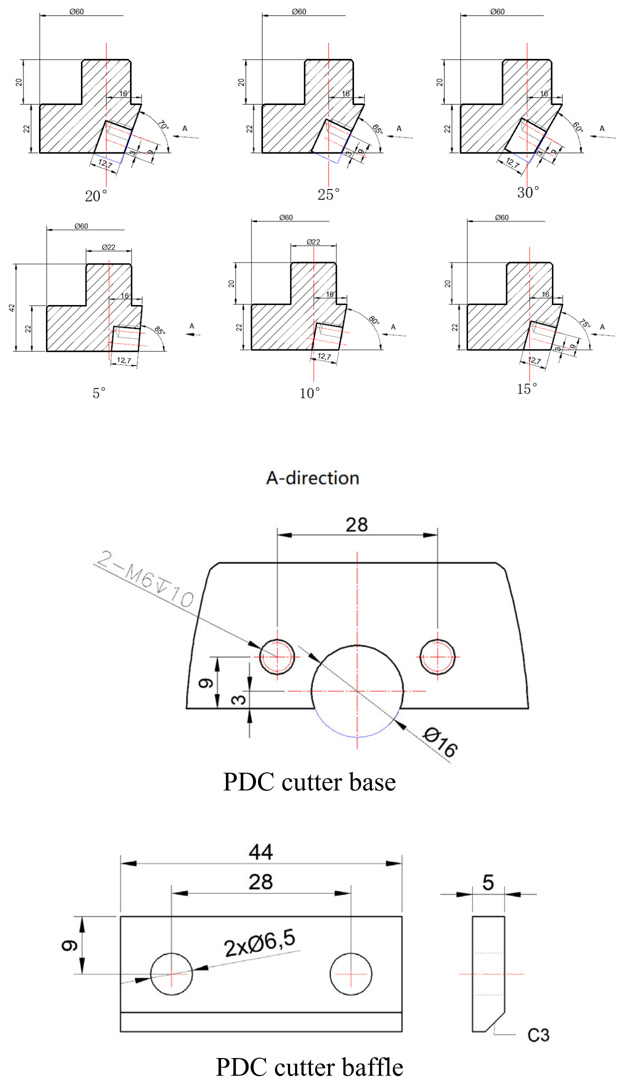


Figure 7. Two-dimensional design drawing of cutter base

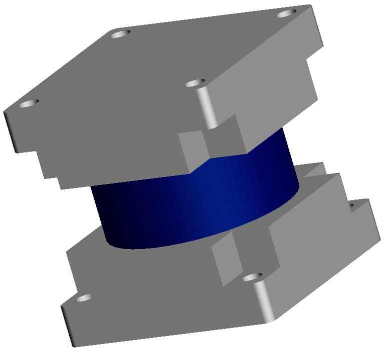


Figure 8. Support seat and sensor bracket

3.2. Experimental rock sample

The rock samples used in the experiment are sandstone and limestone, and the rock size is a 300mm cube, as shown in Figure 9.

(a)Sandstone

(b)Limestone

Figure 9. Experimental rock sample

3.3. Results of PDC rock fracture experiment

3.3.1. Limestone

Figure 10 shows the cut marks morphologies of PDC cutters when the penetration depth of PDC cutters is 0.5mm, 1.2mm and 1.6mm, respectively, and the cut marks morphologies of PDC cutters when PDC cutters are carried out straight scraping after wave rock breaking. It can be seen that the rock disintegration along the edge of the cut mark track is not obvious at a relatively deep snack, and the rock disintegration area along the cut mark track edge is gradually serious with the increase of the depth of eating. This is mainly because limestone is a kind of hard brittle rock, and it is easier to produce volume breakage when the rock is eaten at a great depth than when it is eaten at a great depth.

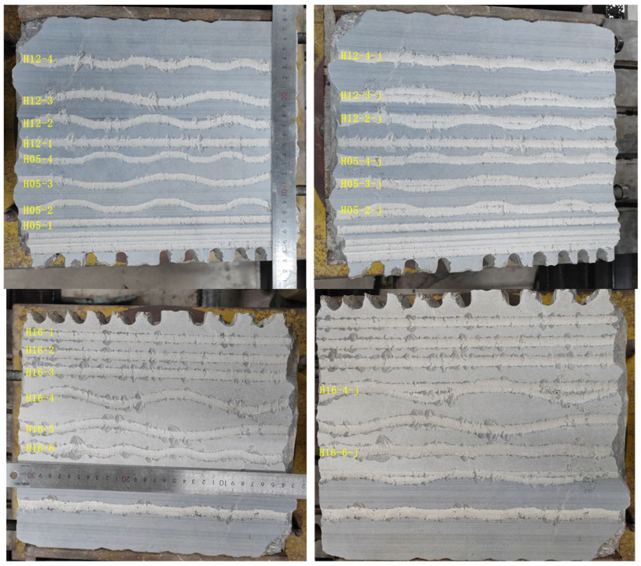


Figure 10. Appearance of limestone scraping marks

Figure 11 shows the cuttings collected after cutting limestone at different feeding depths. It is also proved from the cuttings morphology that with the increase of eating depth, the larger the cuttings produced, the more obvious the volume fragmentation of rock. From the horizontal view of the figure, especially when the penetration depth is 1.2mm and 1.6mm, volume breakage is more likely to occur under the condition of small value and high frequency swing.

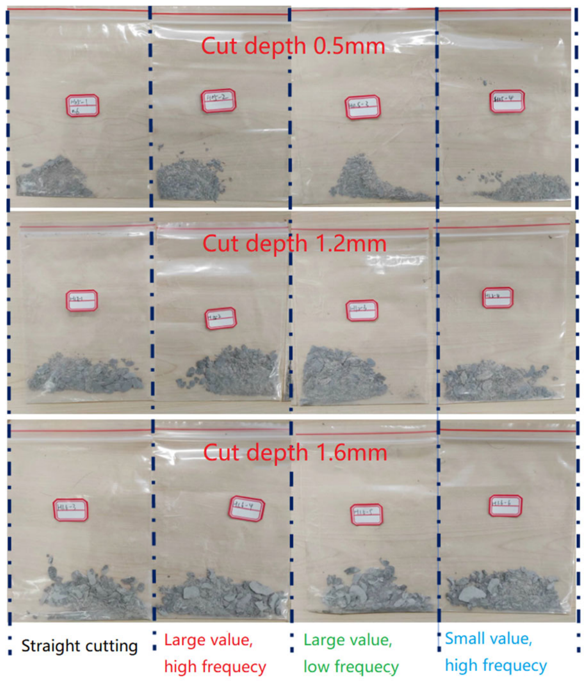


Figure 11. Limestone debris

Figure 12 shows the three-way load law on PDC cutters during linear scraping and swinging scraping. As can be seen from the figure, the order of three-way load is axial force > tangential force > radial force. Since PDC cutters have no side Angle during the experiment, the radial force fluctuation range of PDC cutters is not large in straight scraping, while the tangential force fluctuates up and down in zero load in swinging scraping.

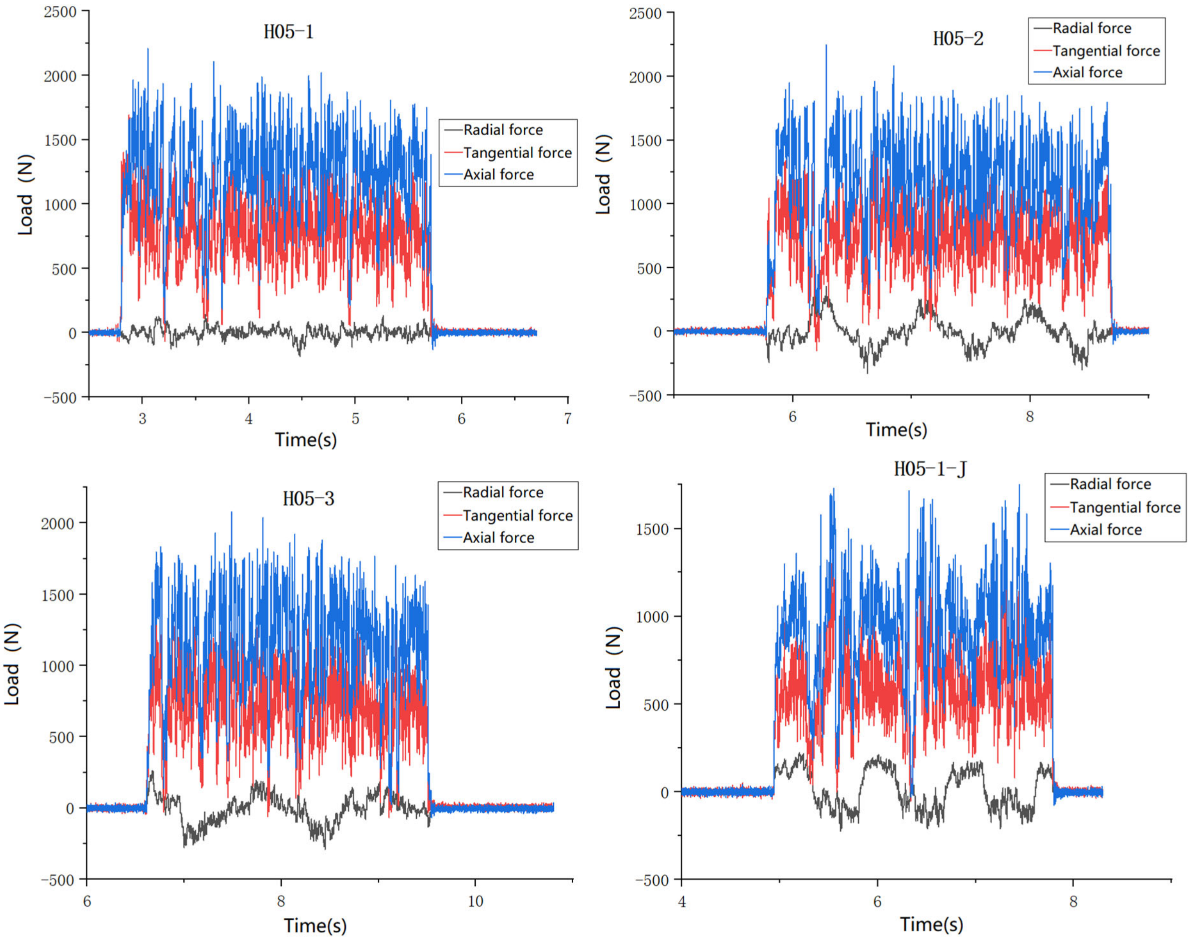


Figure 12. Comparison of three-way load between linear and oscillating scraping

Figure. 13 shows the change law of tangential load and axial load of PDC cutters when the cutting depth is 0.5mm, 1.2mm and 16.mm, respectively. As can be seen from the figure, tangential load and axial load show an approximate linear increase trend with the increase of penetration depth. The axial load is about 1.8 times of the tangential load under the same penetration depth.

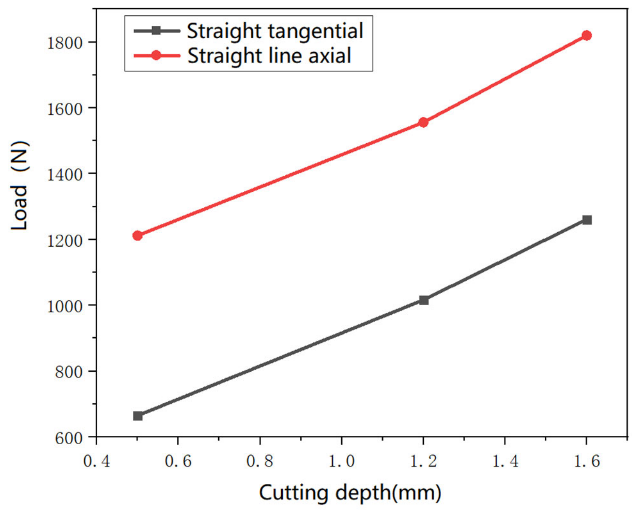


Figure 13. The relationship between tangential load and axial load and depth of straight scraping

Figure 14 shows the comparison of radial loads on PDC cutters of linear scraping and swinging scraping under different feeding depths. The fluctuation range of PDC cutter radial load increases with the increase of feeding depth, whether it is linear scraping or swinging scraping. Under the same cutting depth, large amplitude and small frequency swinging scraping mode has the largest radial load, followed by small amplitude and small frequency swinging scraping mode, and the minimum is large amplitude and small frequency swinging scraping mode. Under the condition of the same cutting depth, the fluctuation amplitude of radial load of swinging scraping mode is significantly higher than that of straight scraping mode, which is also the main reason why PDC cutters are easy to collapse during vortex drilling.

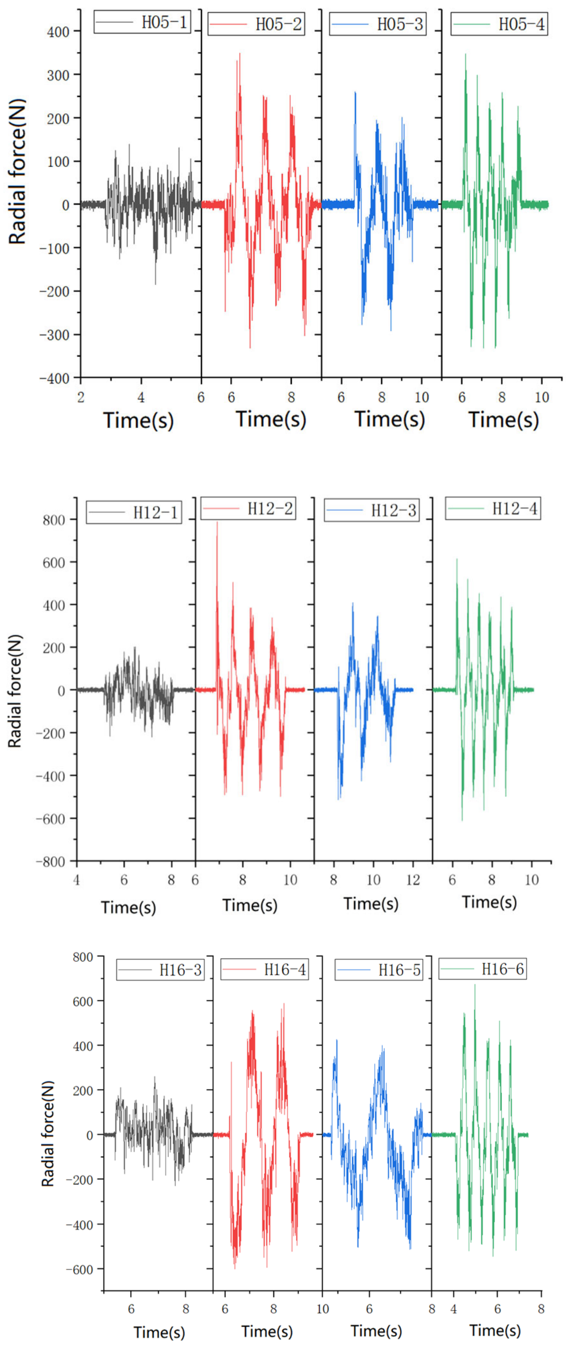


Figure 14. Linear and swinging scraping radial load (depth: 0.5mm, 1.2mm, 1.6mm)

Figure 15 shows the tangential load comparison between PDC cutters of linear scraping and swinging scraping under the conditions of 0.5mm, 1.2mm and 1.6mm feeding depth. It can be seen that for the same cutting depth, the tangential force generated by swinging scraping mode is almost the same as that generated by straight scraping mode, mainly because the contact area between cutter surface and rock does not change during the cutting process. So swing scraping has little effect on tangential load.

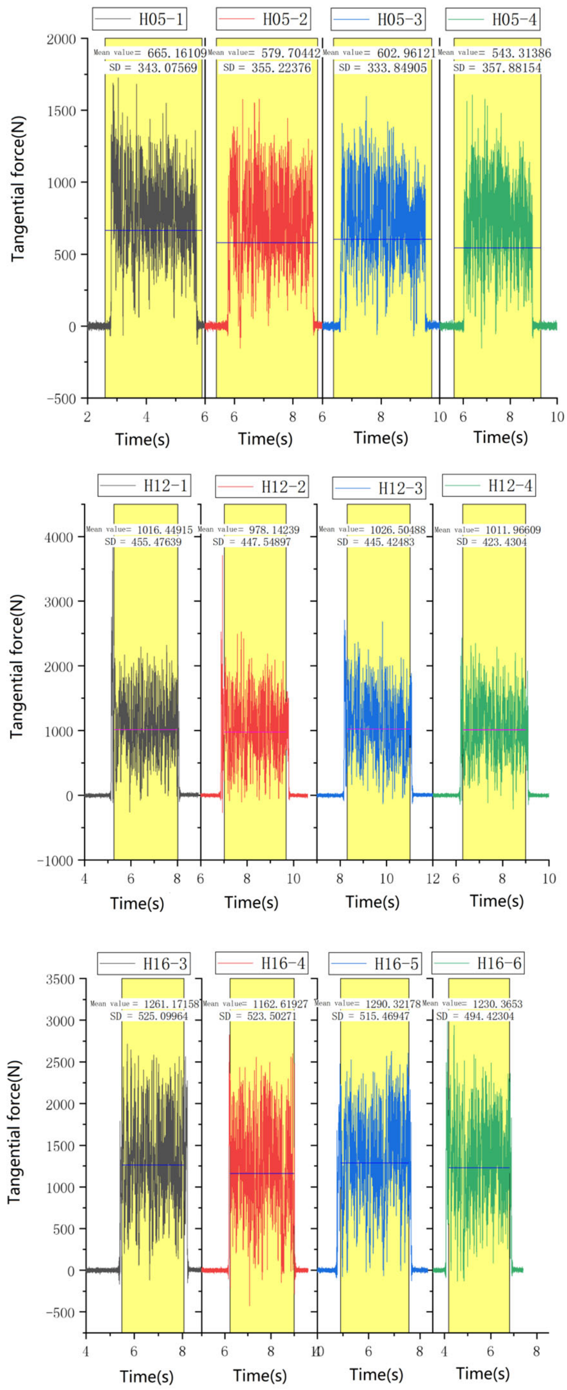


Figure 15. Linear scraping and swing scraping tangential load (depth of 0.5mm, 1.2mm, 1.6mm in turn)

Figure 16 shows the comparison of axial load on PDC cutters of linear scraping and swinging scraping under the conditions of 0.5mm, 1.2mm and 1.6mm cutting depth. It can be seen that for the same cutting depth, the axial load generated by swinging scraping mode is almost the same as that generated by straight scraping mode. So swing scraping has little effect on tangential load.

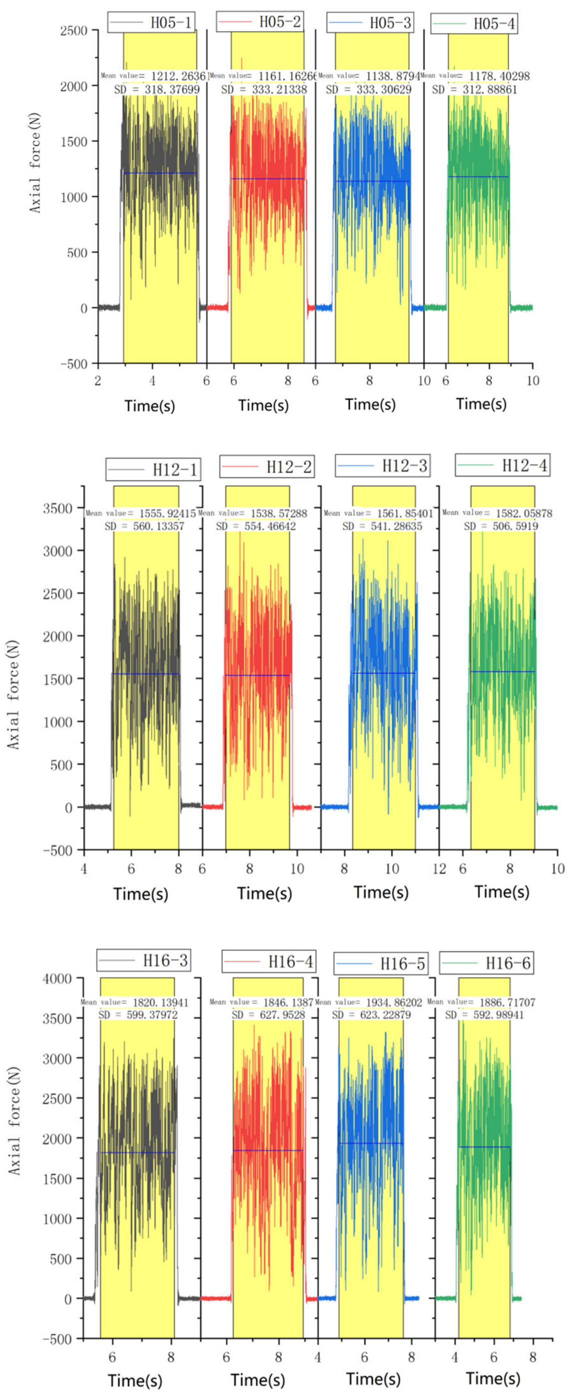


Figure 16. Axial load of linear scraping and oscillating scraping (depth: 0.5mm, 1.2mm, 1.6mm)

Figure 17 shows the variation law of three-way load when linear scraping is performed again on the scraping trajectory with different swinging modes, which is the so-called compound scraping mode. The three-way load of the combined scraping mode is lower than that of the single swinging scraping mode. In the composite scraping and cutting mode, both tangential load and axial load have periodic fluctuations, which is mainly because the curved scraping marks have been formed in the swinging scraping, and then in the straight scraping, PDC cutter load will have a certain decrease at the scraped marks. Therefore, the bit helps to reduce the working load of PDC cutter in terms of rock breaking load during vortex drilling.

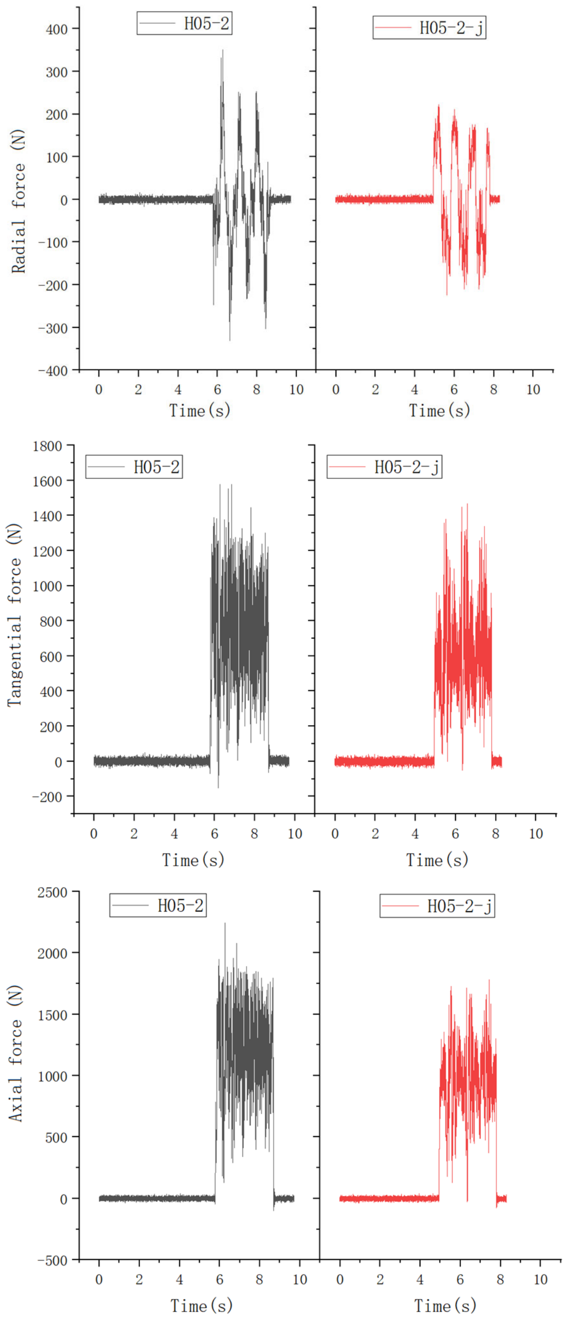


Figure 17. Three-way load for linear scraping after swinging scraping

(depth: 0.5mm, 1.2mm, 1.6mm)

In order to measure the efficiency of rock breaking, it is measured by the work done per unit volume of rock breaking, that is, the crushing work. Figure 18 shows the contrast law of crushing specific work under tangential load under different scraping and cutting methods. It can be seen that the crushing specific energy of swinging scraping mode is smaller than that of straight scraping mode. There is little difference between swinging 1 mode and swinging 2 mode, and the crushing specific energy of swinging 3 mode is the smallest. This is mainly because PDC cutters can cause large volume crushing of rocks under swinging rock breaking mode, which can also be seen from the preceding cuttings form. Therefore, in terms of rock breaking energy, swing rock breaking is helpful to improve the crushing efficiency of rock.

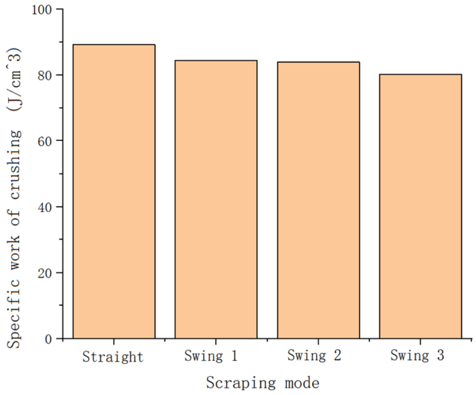
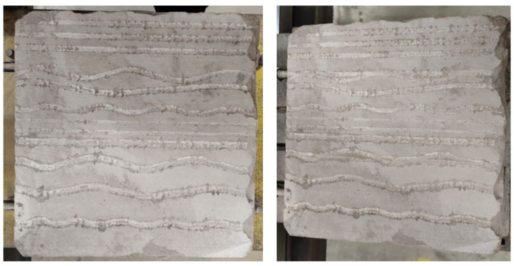


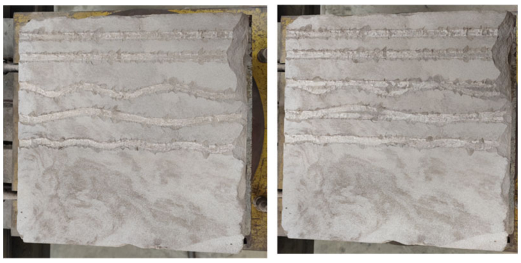
Figure 18. Straight line and swing specific work of crushing

3.3.2. Sandstone

Figure 19 shows the cut marks morphologies of PDC cutters when the sandstone is broken at the penetration depth of 0.5mm, 1mm and 2mm, and the cut marks morphologies of PDC cutters when the rock is broken in a straight line after swinging. Because sandstone is softer than limestone, the volume breaking of rock side is not obvious.



1mm and 1.5mm cutting depth scratches



2mm scratch mark

Figure 19. Scratch the sandstone

Figure 20 shows the sandstone cuttings collected by different scraping methods.

Figure 20. Sandstone cuttings

Figure 21 shows the changes of the corresponding three-way load when the sandstone is cut in a straight line at the depth of 1mm, 1.5mm and 2mm. It can be seen that, under the condition of 15 degrees of front dip Angle set in this experiment, tangential load and axial load are basically the same when scraping sandstone. For scraping and cutting under other dip Angle conditions, the changes of tangential load and axial load need further supplementary experiments.

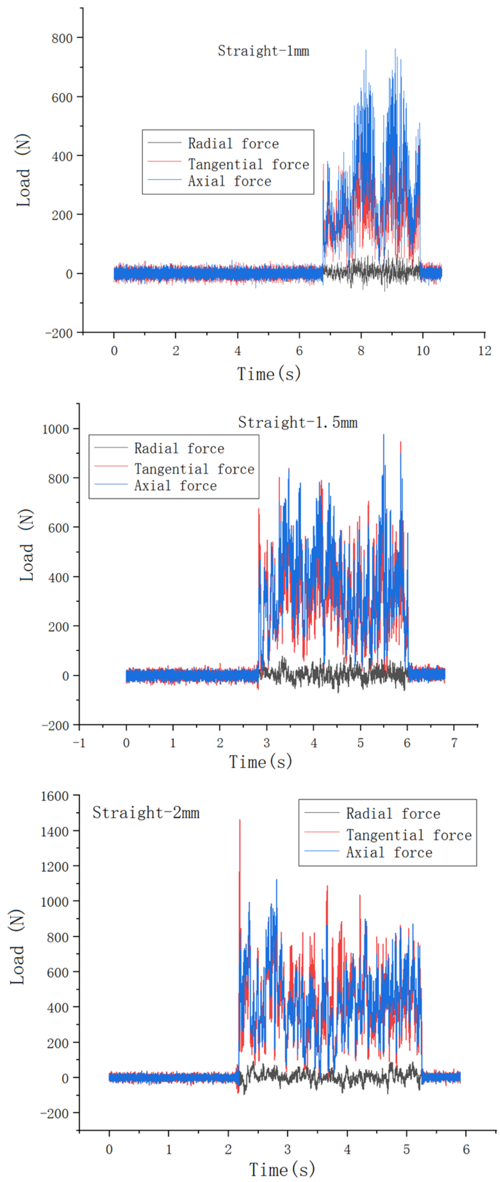


Figure 21. Linear scraping and cutting triaxial load at different cutting depths

Since the axial load and tangential load of PDC cutters were basically the same when sandstone was scraped in a straight line with an Angle of 15 degrees before, the mean value of tangential load under different cutting depth during linear scraping was statistically analyzed here, and the variation law of tangential load or axial load with cutting depth could be obtained, as shown in Figure 22. As can be seen from the figure, when the sandstone is scraped in a straight line, the axial load or tangential load of PDC cutter increases approximately linearly with the increase of the depth of cutting.

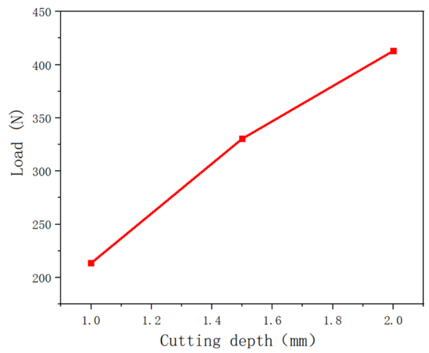


Figure 22. Variation of axial and tangential loads on broken sandstone with depth of cutting

Figure 23 shows the variation law of PDC radial force in linear scraping and swinging scraping modes under different cutting depths. It can be seen that when scraping sandstone, the fluctuation range of radial load increases with the increase of cutting depth under the same scraping mode. Under the condition of swinging scraping, the fluctuation of radial scraping load is the smallest with large amplitude and low frequency. At the depth of 1mm and 2mm, the fluctuation range of radial scraping load of small amplitude and high frequency is greater than that of large amplitude and high frequency, and at the depth of 1.5mm, the fluctuation range of radial load of small amplitude and high frequency scraping is the largest.

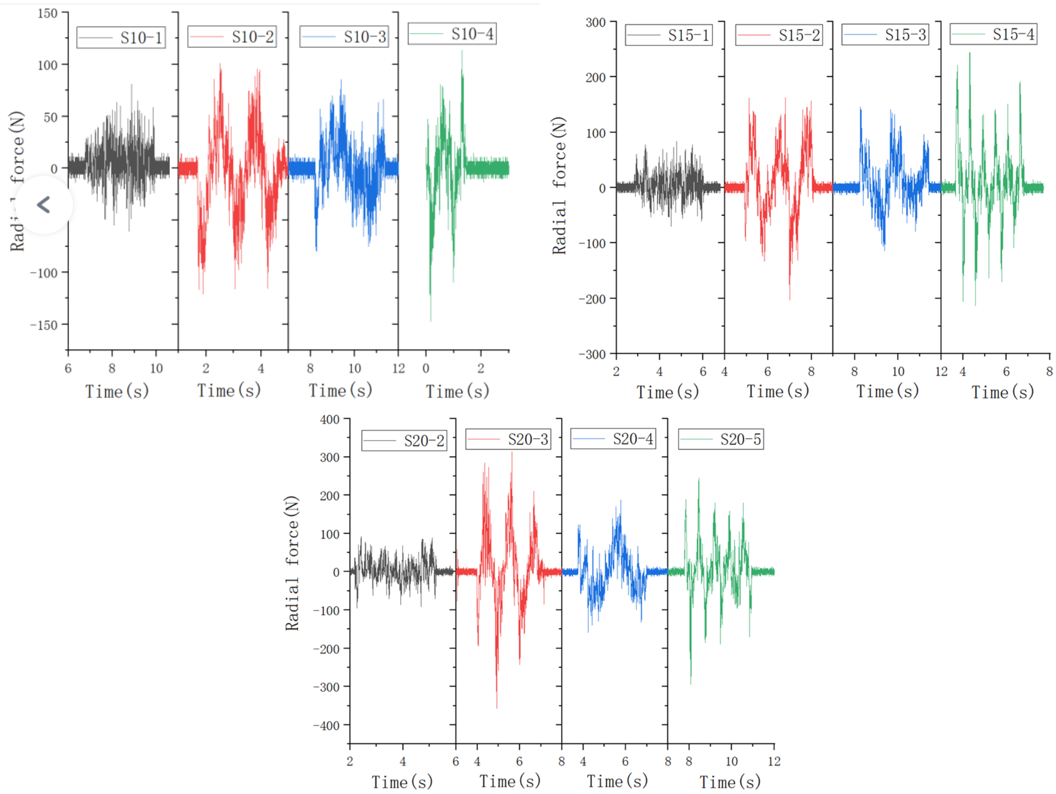


Figure 23. Variation of radial load on broken sandstone

Figure 24 shows the variation law of tangential load and axial load during linear and oscillating scraping under different penetration depths. It can be seen that the tangential force and axial force of linear scraping and swinging scraping are not much different.

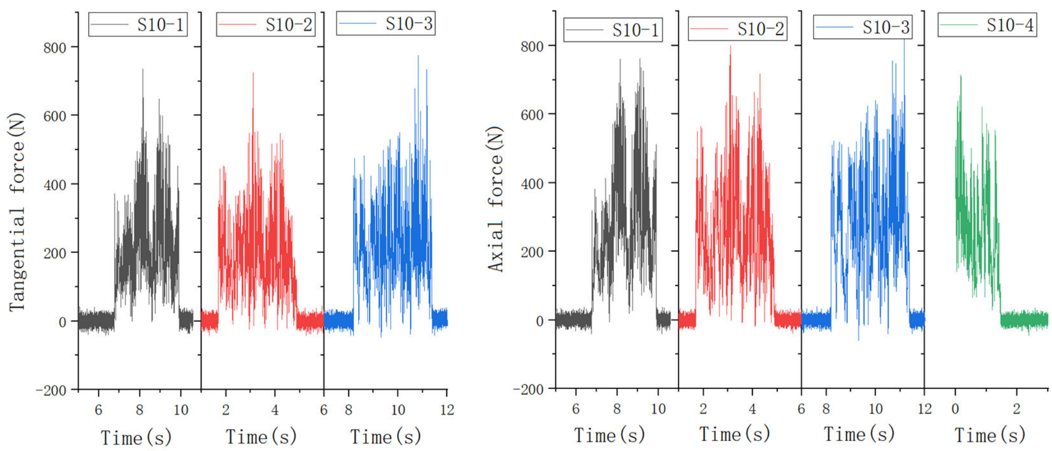


Figure 24. Comparison of tangential and axial loads for linear and oscillating scraping

Figure 25 shows the tangential load comparison between linear scraping and linear scraping after large scale and low frequency scraping. The tangential force of linear scraping is relatively stable on the whole, while the tangential load of linear scraping after swinging fluctuates obviously up and down, and the area where the tangential load decreases is the rock cut during swinging scraping. From the point of view of the average tangential load, on the basis of swinging scraping again linear scraping, tangential load has a large decline, especially after small amplitude, high frequency swinging scraping straight scraping, tangential load reduced by about 70%. Therefore, the cutting load of PDC bit can be significantly reduced under rotary motion.

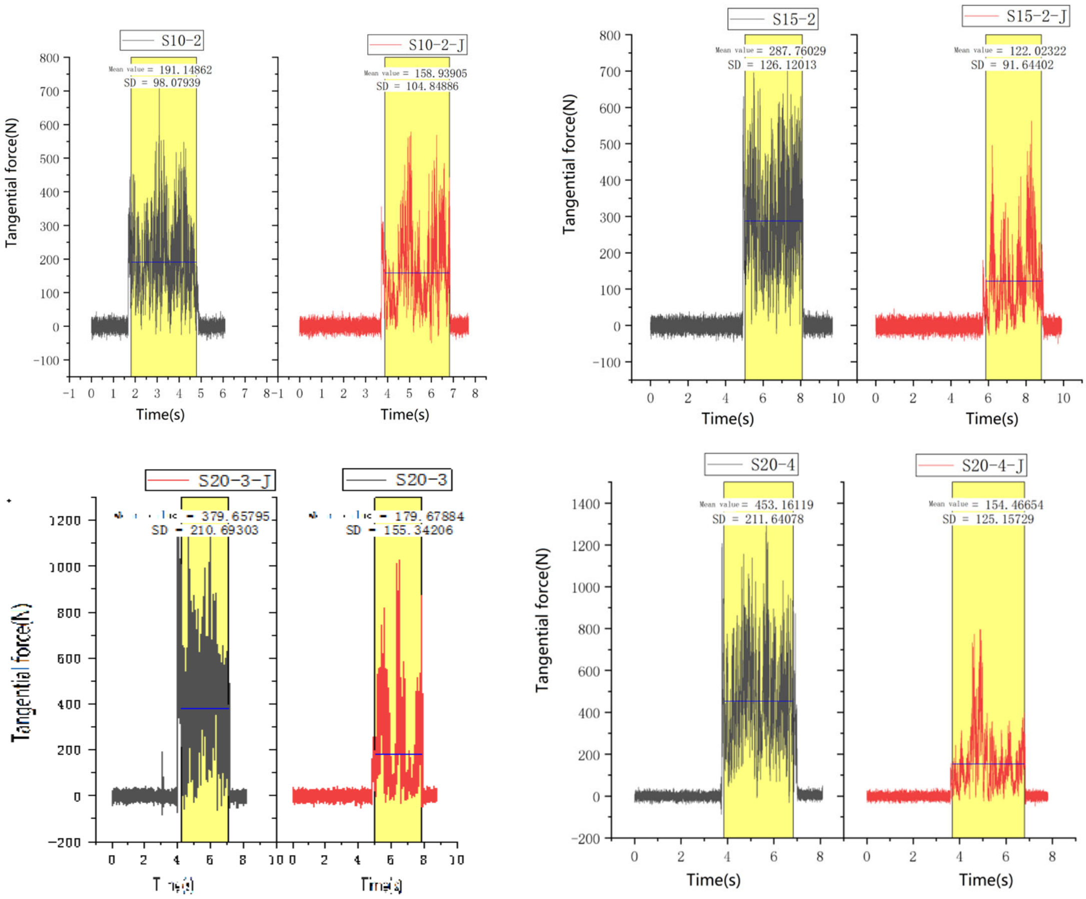


Figure 25. Tangential load of straight line scraping of sandstone after swinging scraping

Figure 26 shows the comparison of rock breaking specific work under tangential loads of straight scraping and different swinging scraping methods. It can be seen that in terms of rock breaking energy, swing rock breaking is helpful to improve the crushing efficiency of rock.

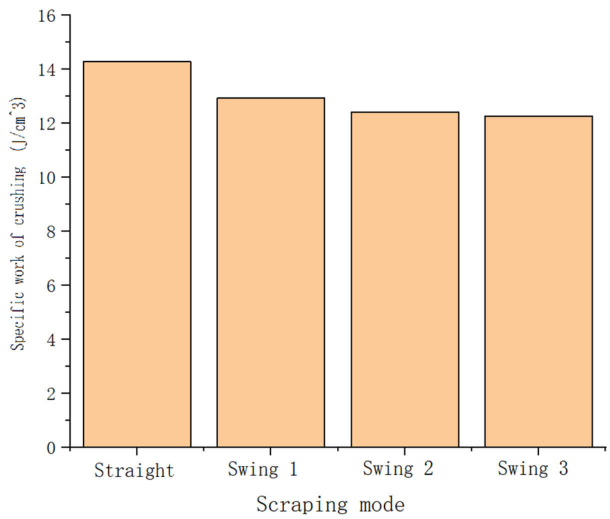
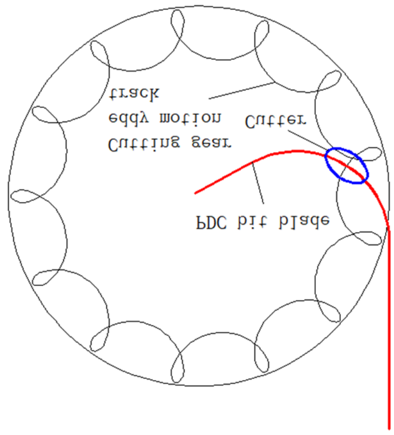


Figure 26. Straight line and swing specific work of crushing

4. Discussion and Analysis

There is also room and possibility for the bit geometric center to deviate from the axis of the hole when the hole diameter is enlarged (i.e., hole radius increment δ>0). But in the actual drilling process is inevitable to enlarge the hole diameter, so there must be some geometric center of the bit deviated from the axis of the hole rotation state. When the geometric center of the bit deviates by δ distance from the wellbore axis, the bit gauge structure (active or passive gauge) is in contact with the wellbore wall. If there is no slip, the bit rotates at the instantaneous center of rotation at the contact point, rather than the geometric center of the hole. Just like a car tire, its instantaneous center of rotation is the tire's point of contact with the ground, not the axle. One of the remarkable things about motion is that once it starts, it's hard to stop. There are two main factors that make the rotations difficult to control. One is that the huge centrifugal force generated at high speed of rotation throws the bit towards the wall of the shaft, creating extra friction in contact with the wall and strengthening the rotations. This centrifugal force, which is proportional to the square of the rotational speed, is greatly affected by high rotational speed and is usually sufficient to overcome rotational inertia and "throw" the bit off the axis. The second is the center of rotation. The instantaneous center of rotation of the bit during rotation is no longer the geometric center of the bit, but the contact point with the shaft wall, which is contrary to the kinematic property of the rotary body. At this point, the cutters' stress and bottom hole coverage will be significantly changed, and this trend is becoming more intense. Therefore, when there is a dynamic side force on the bit, it can cause the bit to rotate away from the geometric center of the hole. The deviating bit frequently collides with the borehole wall to cut a larger hole, increasing the eddy distance, resulting in more profound changes in the motion and force of the cutter, and finally leading to uneven wear, impact fragmentation, and bond layer loss.

Under ideal drilling conditions, the bit's cutters follow a spiral pattern similar to a thread, drilling downward from the previous cut, with a series of concentric circles between them. If the rotation is controlled to allow for slight lateral vibration, the cutters will deviate from their original trajectory, and the radial direction of the bottom hole profile will be marked with micro-cuts that cross the trajectory. As the cutter cuts through the rock, these micro-cuts become "unloading slots" (see image below). The existence of "unloading groove" reduces the speed of cutter wear, improves the cutting efficiency, and the broken cuttings are finer.



Since the cutters of PDC bit mainly rely on the cutter edge on the cutter surface to break rock, in the presence of transverse force, the side of the cutters should also be affected by the rock, so as to participate in the cutting of rock. This requires changing the shape of the cutter side or improving the material properties of the cutter to ensure that the side can cut rock without damaging the cutter.

Acknowledgment

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