

Study on rock breaking mechanism of PDC bit with rotating module

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Highlights:

1. A rotating modular PDC bit is proposed, the new bit realizes local cross scraping and improves rock breaking efficiency;

2 Through unit experiments, the author studies the changing rules of the rotation speed and force of the rotating module with the module's the journal angle and the side angle.

3. Compared with the conventional PDC bit, the rate of penetration (ROP) of rotating modular PDC bit is increased by 15% and the Mechanical specific energy (MSE) is reduced by 14%.

Abstract: In view of the problems of low ROP, short bit life and high energy consumption of bits in deep and difficult formations. Basing on the 360° rotating teeth and disc PDC bit, a rotating modular PDC bit is proposed. The rock breaking efficiency of the bit is improved by "cross scraping" of the rotating module element (RME) and fixed cutting teeth. In addition, the rotating module element works alternately, which cools the cutting teeth in time, slowing the wear of the cutting teeth and prolongs bit life. This paper introduces the structural characteristics and working principle of the novel bit, and carries out variable parameter experiments on the rotating module element (side angle, journal angle, and tooth arrangement density, etc.) The experimental results show that the rotating speed of the rotating module element increases with the increase of the side angle, and decreases with the increase of the axial angle. The variation rules of cutting load and MSE of rotating module element under different structural parameters are studied. The indoor test shows that the ROP of rotary modular PDC bit is increased by 15% and the MSE is reduced by 14%. It implies that the "cross scraping" of the rotary module element and the fixed cutting teeth can reduce the rock breaking specific work, and provide theoretical basis and support for the design of the subsequent rotary modular PDC bit.

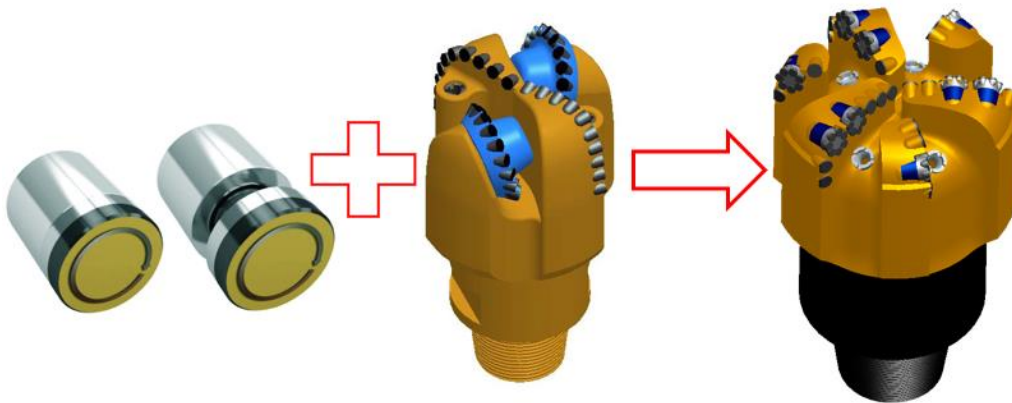
Key word: Rotating module; Rock breaking mechanism; Alternate work

1. Introduction

For deep well and ultra deep well, the drilling cost of deep formation accounts for a considerable proportion in the total drilling cost (Zhu, H.Y. et al., 2019; Dan Scott. 2015). The low drilling rate of deep formation has seriously affected the well construction period and drilling cost of deep well and ultra deep well. Polycrystalline diamond compact bit (PDC bit) is the most important type of bit in oil and gas drilling. Its drilling footage has reached more than 92% of the global total drilling footage (Luc Perner et al., 2012; H. Santos et al., 2000). For PDC bit, cutting tooth technology and bit structure form are important factors affecting rock breaking efficiency of PDC bit (Jiang, M.H et al., 2009; Zhu H.Y. et al., 2015). In order to improve the rock breaking efficiency and service life of the bit, scholars at home and abroad have carried out a lot of relevant research, among which the disc PDC bit with cross scraping is a composite bit which combines the fixed cutting structure with the cutting structure of the disc cutter, The offset angle of the disc cutter on the cross-cut PDC bit is very large. When the drill bit is rotated and drilled, the disc cutter rotates

43 at a low speed. After the cutting teeth on the disc cutter are slowly pressed into the rock, a longer
44 circumferential slip and radial slip are performed on the rock, and then the rock at the bottom of the
45 hole is slowly cut out to form a spiral scraping trajectory. The teeth alternately scrape the broken
46 rock at the bottom of the well in a slow alternating pattern. This spiral scraping trajectory overlaps
47 with the concentric circle trajectory of the fixed cutting teeth of the fixed cutting structure.
48 (Yang,Y.X. et al., 2017; Yang,Y.X. et al., 2018). In the drilling process, the cutting teeth on the disc
49 cutter work slowly and slowly alternately to reduce the thermal wear. At the same time, the way of
50 cross scraping is conducive to cutting teeth into the formation But the cutterhead cutting structure
51 needs an independent support, which occupies the precious space of tooth distribution on the bit.
52 For 360 ° rotary bit, the cutting teeth can rotate freely in the process of rock breaking, which can
53 avoid the occurrence of cutting eccentric wear and prolong the cutting life of the cutting teeth(Li,M.,
54 2017; Li,M. et al., 2017). The application of rotary tooth technology in the development of Saudi
55 Arabia's natural gas has significantly increased the bit penetration and drilling speed, When the
56 rotary bit drilled into sandstone, it achieved a record of 160.2m, and the ROP reached 4.53m / h.
57 The ROP was increased by 76% compared to the maximum ROP of ordinary PDC bits in the same
58 well section(Platt J, et al., 2016).However, due to the limitation of the size of the rotating teeth, the
59 rotating axis of the teeth is too small, so the ability of the cutting teeth to bear the impact load is
60 weak(Mostofi M. et al., 2013).

61 On the basis of 360 ° rotating teeth and disc PDC bits, a rotating modular PDC bit is proposed
62 in this paper. As shown in Fig. 1, the module teeth are used to work in turn slowly, so that the cutting
63 teeth can be sufficiently cooled, and the cutting teeth on the module can be evenly worn, thus
64 prolonging the service life of the cutting teeth. At the same time, in the radial coverage area of the
65 module, the rotating module teeth and the fixed cutting teeth intersect By scraping and cutting the
66 broken rock with fork, the protruding rock ridge can be formed naturally, which can improve the
67 invasion ability of cutting teeth and the rock breaking efficiency of bit.



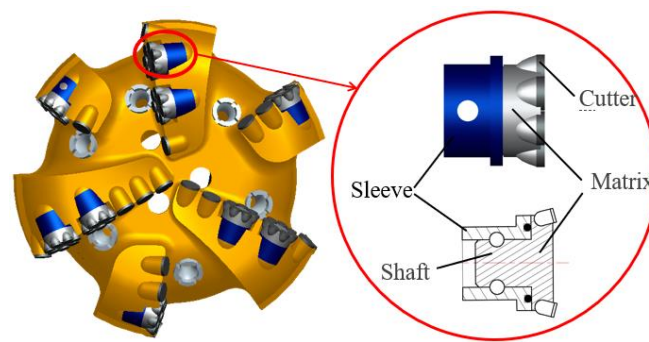
68
69 **Fig. 1 Rotary modular PDC bit**

70 **2. Structure characteristics and working mechanism of PDC bit with** 71 **rotating module**

72 **2.1 Structural features of rotary modular PDC bit**

73 The difference between the rotary modular PDC bit (as shown in Fig. 2) and the conventional
74 PDC bit is that the rotary modular cutting element is introduced into the cutting wing of the fixed

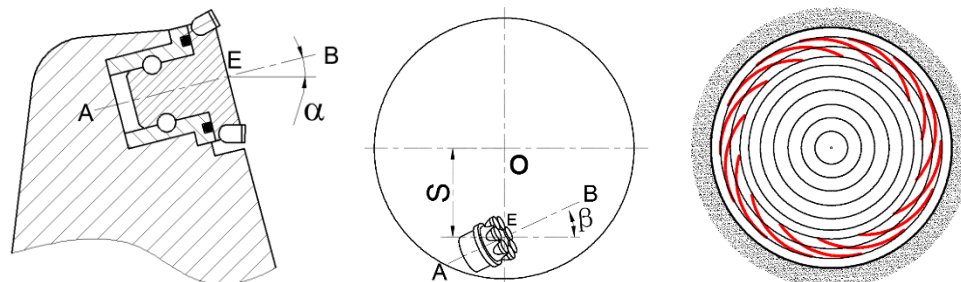
75 tooth PDC bit. The rotary modular cutting element is composed of the matrix (the matrix and the
 76 shaft are integrated), the cutting teeth, the shaft sleeve, etc., which organically combines the
 77 dynamic and static cutting structures to realize the local cross rock breaking and give full play to
 78 the advantages of PDC tooth rock breaking Each cutting tooth on the matrix alternately scrapes the
 79 rock to achieve uniform wear in each area of the same cutting module element; each cutting tooth
 80 interacts with the rock briefly and discontinuously during the working process, with small heat
 81 output and timely heat dissipation, which is not easy to generate thermal wear, so as to extend the
 82 life of the drill head. For the cutting teeth with small diameter, the contact area between a single
 83 tooth and the rock is small and the rock breaking ratio is small High pressure, easy to eat into the
 84 rock, the rotating pair of the rotating module element is set between the base body and the shaft
 85 sleeve, and there is no need to specially set the bearing support or bearing structure on the blade
 86 body, so that the structure of the drill bit is more simple, compact and reliable.



87
88 **Fig. 2 Structure diagram of rotary modular PDC bit**

89 **2.2 Working mechanism of rotary modular PDC bit**

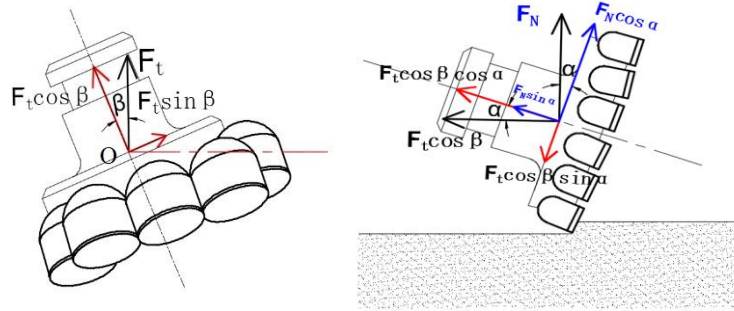
90 When the rotary module element is set with a certain side angle, the teeth on the module
 91 element interact with the rock during the drilling process. Due to the existence of the side angle, the
 92 moment generated when the module rotates is large enough to overcome the resistance of the rock,
 93 then the module element will rotate, and the corresponding structural parameters of the module
 94 element (journal angle α , side angle β , positioning radius S) As shown in Fig. 3. The module element
 95 rotates under the drive of rock, and the trace scraped at the bottom of the well is helix, because the
 96 module has circumferential slip and radial slip, which makes the cutting teeth in this area (assuming
 97 that the module is arranged in the outer 1 / 3 area of the bit crown) and the fixed cutting teeth form
 98 a local cross scraping (schematic diagram of bottom hole track, as shown in Fig. 3 (c)), where the
 99 red track is the rotating die This kind of rock breaking method can significantly improve the rock
 100 breaking efficiency of the bit.



101
102 (a)The journal angle of module element (b) The side angle and positioning radius of module element (c)The schematic diagram of well bottom track

103
104 **Fig. 3 Structural parameters and bottom hole diagram of module element**

105 Whether the rotating module can rotate depends on whether the driving torque can overcome
 106 the friction of the bearing and the force of some module teeth breaking the rock. The driving force
 107 of module element rotation comes from the component of tangential force generated by the
 108 interaction between module element and rock in the direction of side angle. As shown in Fig. 4, the
 109 component force $f_t \sin \beta$ of the tangential force F_t along the side angle direction is the driving force
 110 F_0 of the module; because of the existence of the axial inclination, the axial force F_N and the
 111 tangential force F_t generate the component forces $F_n \sin \alpha$ and $F_t \cos \beta \sin \alpha$ along the module axial
 112 direction, and the component forces $F_n \cos \alpha$ and $F_t \cos \beta \sin \alpha$ along the module element radial
 113 direction opposite.



114
 115 (a) Schematic diagram of tangential force received by the module
 116 (b) Schematic diagram of component force produced by the module due to axle inclination

117 **Fig. 4 Force diagram of rotating module element**

118 Because the bottom contact of module element interacting with rock is a dynamic process, this
 119 paper discusses the critical state of module element rotation, taking the alternative cutting of one
 120 tooth and two teeth as the research object. In an ideal state, if the bearing friction is small enough,
 121 the friction force to be overcome when the cutting teeth intrude into the rock will be ignored. At this
 122 time, the critical tooth arrangement of the teeth is shown in Fig. 5 (b); the corresponding structural
 123 parameters of the module element are shown in Fig. 5 (a), the diameter of the module element D_1 ,
 124 the diameter of the module element working contour (outer circle diameter) D_2 , the diameter of the
 125 module element small teeth D , and the module element teeth The center distance of is L (that is, the
 126 distance between the centers of teeth of two adjacent modules). According to fig. 5 (a), the center
 127 distance L_0 between A and C in Figure 5 (b) is:

$$L_0 = 2\sqrt{D_1^2 - (D_1 - h)^2} \quad (1)$$

128 Where, h cutting depth, D_1 rotating module diameter.

129 Therefore, in an ideal state, the module can keep continuous rotation as long as the tooth
 130 spacing L of the module cutting teeth is less than L_0 and the side angle $\beta > 0$. However, when the
 131 actual module works, it needs to overcome the friction of the bearing and the force of some broken
 132 rocks. As shown in Fig. 5, this paper takes one and two module teeth working alternately at the
 133 bottom of the well as the research object.
 134

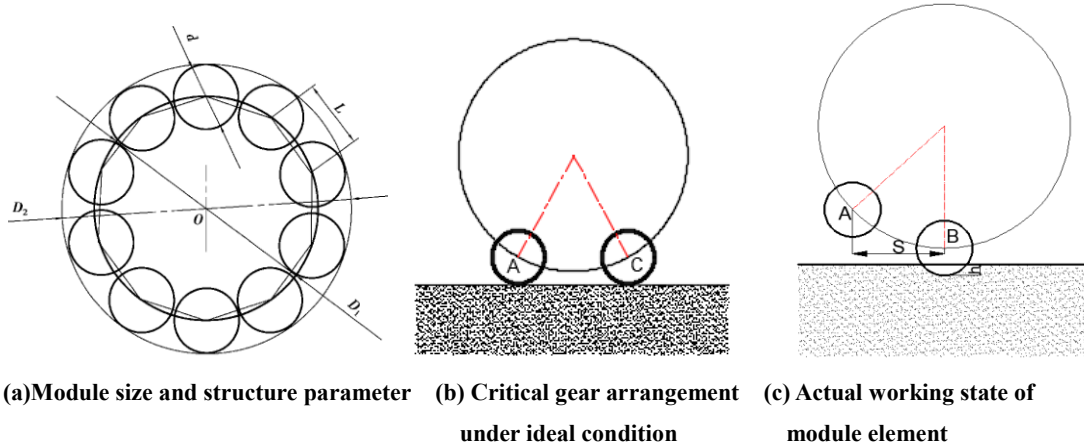


Fig. 5 Schematic diagram of module element cutting

When the module element rotates from A to B, the displacement of the module in the circumferential direction is S , and the displacement in the cutting depth direction is h . at this time, the module overcomes the force of the broken rock, and f_0 is an instantaneous force. With the increase of the cutting depth and the circumferential displacement, f_0 gradually increases; with the increase of the cutting depth, the contact area S_0 between the module teeth and the rock gradually increases, so does the tangential force and the driving force In this paper, the tangential force and the contact area between the module element and the rock are considered to be linear:

$$F_t = k \cdot S_0 \quad (2)$$

Where, k is the contact area coefficient of rock and module element; S_0 is the contact area.

As shown in Figure 5 (b), if the rotating module element is to work continuously, it is necessary to make the driving force F_t generated when the cutting tooth C interacts with the rock greater than the resistance f_0 of the cutting tooth A invading the rock and the friction f_1 generated by the bearing. For the friction force f_1 generated by the bearing is related to the friction coefficient μ and positive pressure N of the bearing, the friction force f_1 generated by the bearing is:

$$f_1 = \mu \cdot (N_1 + N_2) \quad (3)$$

Where μ is the friction coefficient between bearings, N_1 is the positive pressure at the shaft diameter, and N_2 is the positive pressure inside the bearing.

$$\begin{cases} N_1 = F_t \cdot \cos \beta \cdot \cos \alpha + F_N \cdot \sin \alpha \\ N_2 = F_N \cdot \cos \alpha - F_t \cdot \cos \beta \cdot \sin \alpha \end{cases} \quad (4)$$

$$F_0 = F_t \cdot \sin \beta = k \cdot S_0 \cdot \sin \beta \quad (5)$$

$$f_1 = \mu \cdot (F_t \cdot \cos \beta \cdot \cos \alpha + F_N \cdot \sin \alpha + F_N \cdot \cos \alpha - F_t \cdot \cos \beta \cdot \sin \alpha) \quad (6)$$

Therefore, as long as $F_0 > f_0 + f_1$ module can maintain continuous rotation state. Generally, the resistance f_0 of the cutting teeth when they just intrude into the rock is very small, which is ignored in the ideal state. The critical state in Fig. 5 (b) is $F_0 > f_1$.

3. Cutting experiment of rotating module element

3.1 Purpose of the experiment

The working state of the rotating module element is affected by many factors, including the side angle, the journal angle, the number of teeth of the rotating module element and so on. The main purpose of the experiment is to find out the influence rules of various factors on the working state of the rotating module. Through the experiment of the rotating module element, the working state and rock breaking law of the rotating module element are studied, which provides the theoretical basis for the subsequent design of the new PDC bit.

3.2 Experimental equipment and rock samples

The rotating module element scraping experimental equipment includes a shaper testing machine, a three-way force sensor, a rotating module and a data acquisition system (as shown in Fig. 6).

In the experiment, the cutting element is the rotating module element, and the cemented carbide tooth (its model is YG15) is used. The cemented carbide has high hardness, strength and wear resistance. The diameter D of the rotating module tooth is 8 mm. The cemented carbide cutting elements, matrix and shaft sleeve together constitute the rotating module cutting element, as shown in Fig. 7. In the scraping test, the size of sandstone is 300 mm × 250 mm × 250 mm, and the rock mechanical parameters are shown in Table 1.

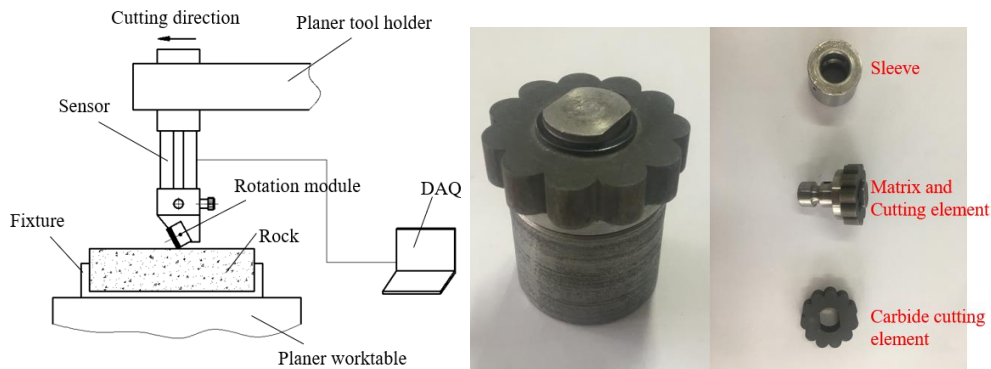


Fig. 6 Scraping experiment of rotating module element Fig. 7 Cutting element of rotating module

Table 1. The primary physical parameters of the rock samples

Rock	Uniaxial compressive strength (MPa)	Shear strength (MPa)	Internal friction angle (°)	Elastic modulus (GPa)	Poisson's ratio
Sandstone	67.548	13.56	38.03	11.54	0.062

3.3 Experiment content

The experiment contents include: different journal angle (0°, 5°, 10°, 15°, 20°, 25°, 30°), different side angle (0°, 5°, 10°, 15°, 20°, 25°), different number of teeth (9, 10, 11, 12, 13). The specific experimental content is shown in Table 2:

Table 2 Experimental Content

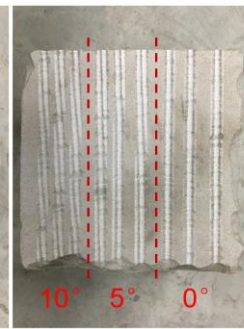
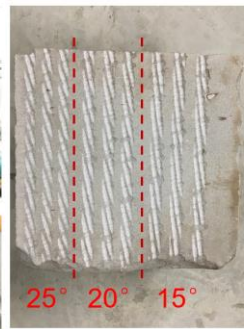
Experiment No.	Experimental Content	The penetration depth (mm)	Cutting speed (m/s)	Experiment Times
#1	The journal angle of the Rotating module (0°~30°)	2	0.3	3

#2	The side Angle of the Rotating module($0^{\circ}\sim 25^{\circ}$)	2	0.3	3
#3	The Number of teeth of rotating module (9~13)	2	0.3	3

190

191 3.4 Experimental method and process

192 First, the rock sample is placed on the rock clamping tool, then the scraping surface of the
 193 rock sample is parallel to the planer table by adjusting the position of the rock sample, the rotating
 194 module and the three-way force sensor are fixed on the planer frame, the position of the planer
 195 frame is adjusted to make the cutting tooth's eating depth specified in the experiment, the channel
 196 of the signal acquisition system is cleared and the sampling is started, and then The testing
 197 machine scrapes the rock sample in a straight line, breaks the rock sample, records the
 198 experimental data through the data acquisition system, collects the broken rock debris, and
 199 completes one experiment. Each experiment is repeated at least three times, and the specific
 200 experimental process is shown in Fig. 8.



201

202 Fig. 8 Experiment process

202 Fig. 9 Craping trace of rotating module element

203

203 3.5 Analysis of experimental results

204 The scraping trace of the rotating module element on the rock is different from that of the
 205 fixed teeth, and the scraping trace of the different side corners is shown in Fig. 9. It can be seen
 206 from the figure that: with the increase of the side corners of the rotating module teeth, the rotating
 207 speed of the rotating module teeth increases gradually, and the number of scratches increases
 208 gradually. Because the side angle and the angle of the axis of the rotating module element will
 209 affect its rotating speed, the relationship between the rotating speed and the journal angle and the
 210 side angle is made as shown in Fig. 10. The diameter of the outer circle of the rotating module
 211 element $D_2 = 35$ mm, the diameter of the small teeth of the module element $D = 8$ mm, and the
 212 number of the small teeth of the module element $n = 11$. The scraping experiment is completed
 213 on the sandstone.

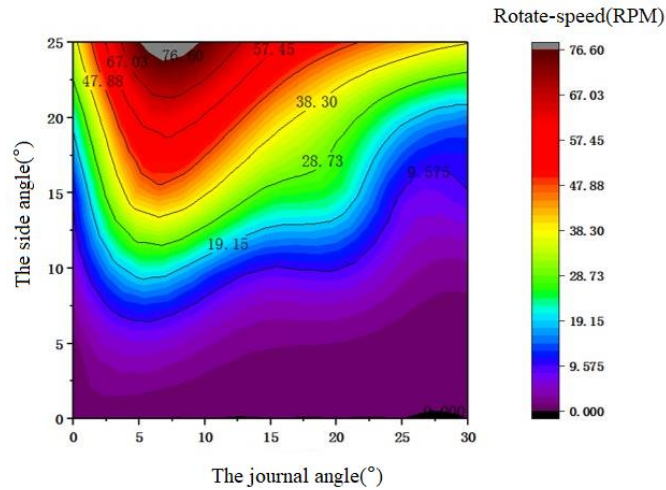


Fig.10 Contour map of rotation module element Rotate-speed

214
 215
 216 When the side angle is 90° , the rotating module element does pure rolling. When the
 217 side angle is 0° , the rotating module element does not rotate and does pure sliding. With the
 218 gradual increase of the side angle, the greater the rotating force of the driving module element
 219 is. When the side angle increases from 0° to 90° under any axle inclination, the rotating
 220 speed increases gradually. When the journal angle increases from 0° to 5° , the rotating speed
 221 of the rotating module element tends to increase. The reason is that when the journal angle
 222 of the module element is 0° , the tooth cylinder of the module element contacts with the rock,
 223 so the module element has to overcome some friction caused by the contact between the tooth
 224 cylinder of the module element and the rock when it rotates. When a small journal angle is
 225 given to the module element, the tooth surface of the cutting tooth first cuts off the rock,
 226 because of a certain journal angle, the cylinder surface of the cutting tooth can avoid too
 227 much contact with the rock, reducing the friction; when the journal angle increases from 5°
 228 to 30° , the rotation speed of the single element of the rotating module decreases gradually,
 229 because the module element receives the reaction force of the rock along the axis of the
 230 module element. The component force of the direction increases gradually, so the force of
 231 driving module element to rotate decreases gradually. At the same time, it needs to overcome
 232 the friction produced by more module element bearings. Therefore, with the increase the
 233 journal angle, the speed decreases gradually.

234 Because of the principle that the module elements work alternately, the load of the
 235 module element is different from that of the fixed PDC teeth. At the same time, the load
 236 variation law of the whole module element also has a great influence on the bearing life. The
 237 experiment shows that the axial force and tangential force of the rotating module element
 238 follow the different side angle conditions. The change rule of the journal angle is shown in
 239 Fig. 11. It can be seen from the figure that when the journal angle is 10° and 15° , the axial
 240 and tangential loads on the rotating module element are relatively small. At this time, the
 241 invasion ability of the rotating module element is better, which is also conducive to extending
 242 the service life of the module element. With the increase of the journal angle, the axial and
 243 tangential loads on the rotating module element increase, and the invasion ability of the
 244 module element decreases.

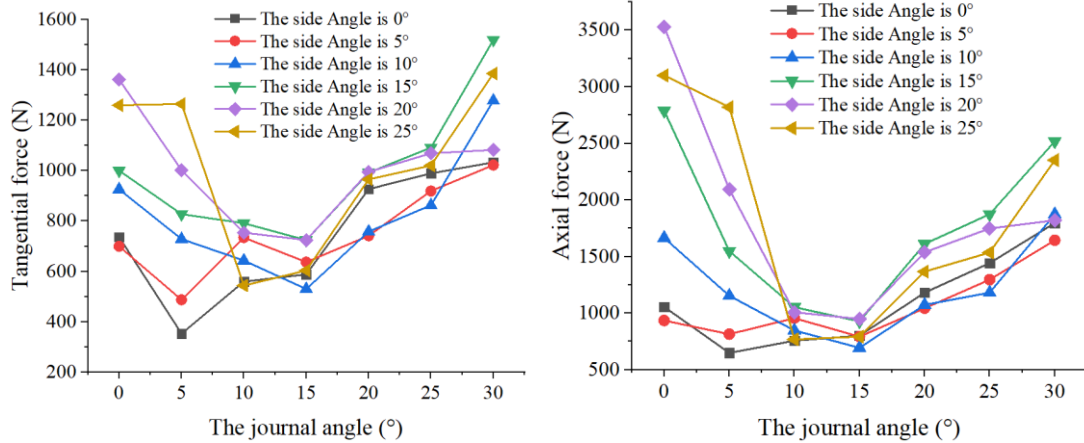


Fig.11 Force of rotating module element

The mechanical specific energy(MSE) of rock, also known as the crushing work per element volume, refers to the energy required to crush the rock per element volume, which is an important index to study the rock breaking efficiency. For the rotating module element, the change rule of its crushing specific work with the side angle and the journal angle is shown in Figure 12 (the diameter of the outer circle of the rotating module element $D_2 = 35$ mm, the diameter of the module element pinion $d = 8$ mm, and the number of the module element pinion $n = 11$). It can be seen from the figure that: with the increase of the side angle, the crushing specific work of the rotating module element increases gradually, and the rock breaking efficiency decreases gradually; with the increase of the journal angle, the MSE of the rotating module element decreases first and then increases, with the journal angle of 10° , the MSE is smaller, and the rock breaking efficiency is higher.

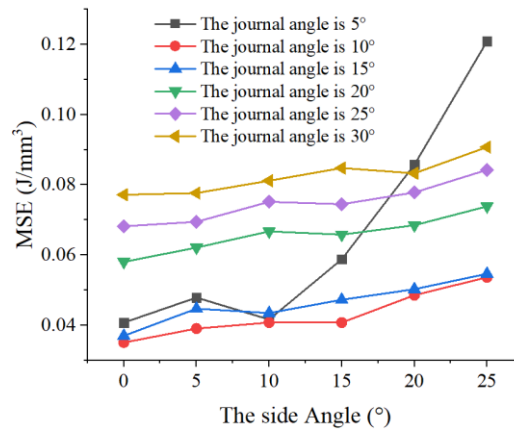
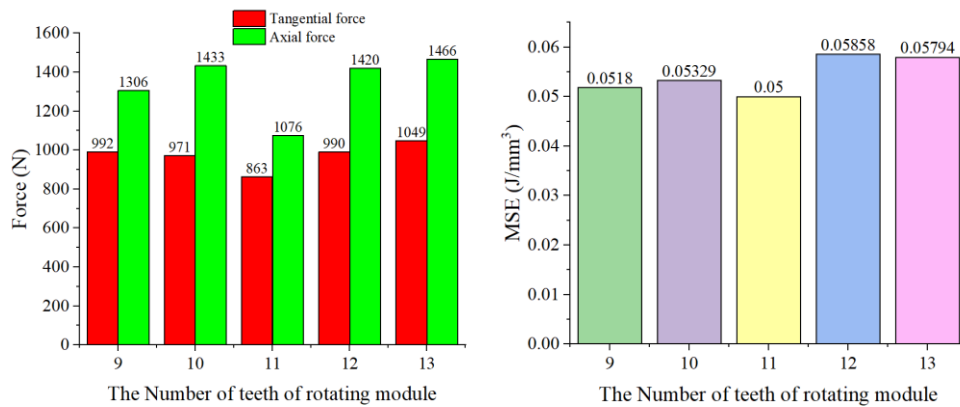


Fig.12 MSE of rotating module element

In order to facilitate observation, the larger the rotation speed of the side angle is higher, and the scraping traces formed on the rock are more obvious. Therefore, the scraping experiments with different tooth distribution density are carried out when the journal angle is 20° and the side angle is 20° . The cutting depth is 2mm, the outer circle diameter of the module element is 35mm, and the diameter of the module single small tooth is $d = 8$ mm. The relationship between module element speed and module tooth distribution density is shown in Figure 13. It can be seen from the figure that with the increase of the number of cutting teeth in the module element, the axial force and tangential force of the module element fluctuate. When the number of cutting teeth n is equal to 11, the tangential force and axial force received by the module are the minimum. At this

269 time, the rock breaking specific work of the module element is the minimum and the rock
 270 breaking efficiency is the highest. In the process of rock cutting, at least two or more cutting teeth
 271 of the module element must be able to touch the bottom at the same time, so as to ensure the
 272 normal rotation of the module element. When the number of cutting teeth of the module element
 273 is small, the spacing between adjacent teeth is too large, resulting in the impact load of the module
 274 during the rotation process; with the increase of the number of cutting teeth, resulting in the rapid
 275 increase of the rotational speed of the module element In this way, the impact load of the module
 276 element increases, which is not conducive to extending the service life of the rotating module
 277 element. Therefore, the optimal number of cutting teeth of the rotating module element is to
 278 enable the module element to rotate stably and slowly. Therefore, it is necessary to optimize the
 279 design when determining the number of cutting teeth of the module element.



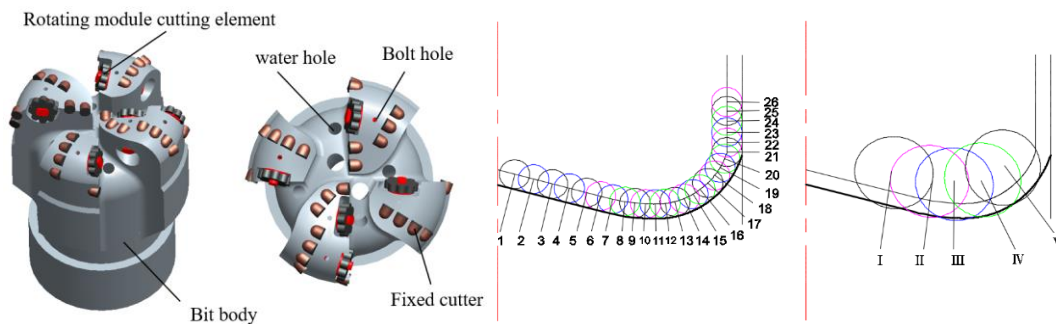
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Fig. 13 Operation of rotation module with different number of cutting teeth

282 4. Laboratory bench test of rotary modular PDC bit

283 4.1 Design and manufacture of rotary modular PDC bit

284 An 8-½-inch experimental bit is designed. The number of blades is 4, the number of rotating
 285 module elements is 5, which are arranged in different radial positions. The diameter of the
 286 working contour of the rotating module element is $D_2 = 35\text{mm}$, the diameter of the module
 287 element teeth is $d = 8\text{mm}$, and the number of n is 11. The structural parameters of the rotating
 288 module element are selected in combination with the element experiments. the journal angle is
 289 15° , the side angle is 15° , the diameter of the PDC cutting teeth is 13.44mm , and the height is
 290 8mm . The experimental drill is shown in Fig.14. The experimental drill controls the rotary cutting
 291 of the rotating module cutting element through the pin.

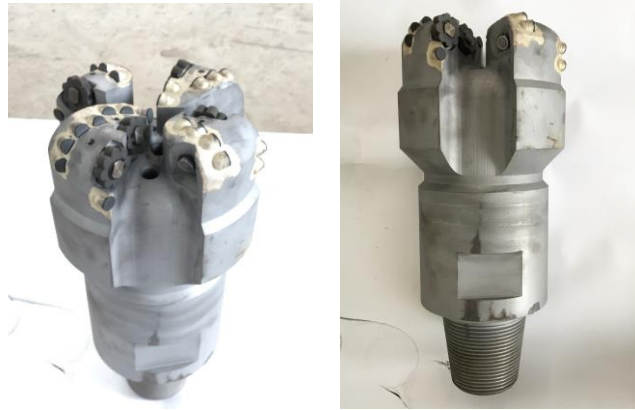


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 293

Fig. 14 three dimensional diagram and tooth arrangement diagram of experimental bit

294 The machining of the cutting teeth of the bearing and the rotating module element adopts
 295 the common lathe and wire cutting to weld the cutting teeth on the fixed wing and the body joint.

296 The experimental bit is shown in Fig.15.



297
298 **Fig. 15 Photo of experimental bit**

299 **4.2 Laboratory bench test process and method**

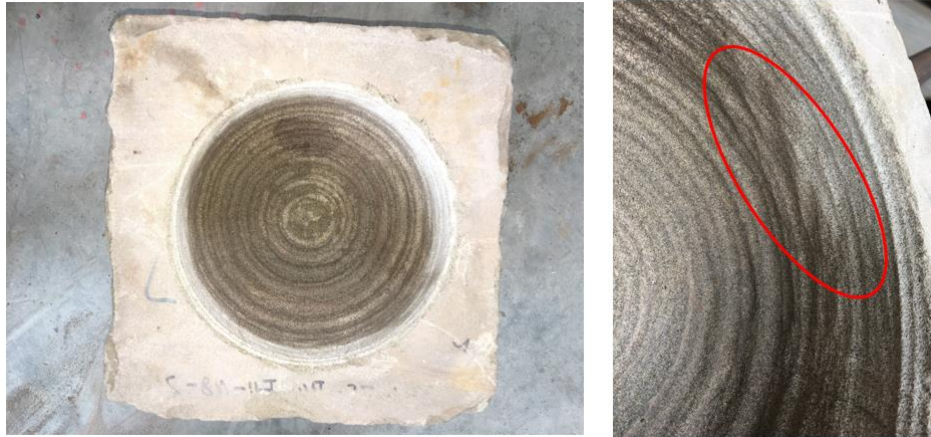
300 In the experiment, By the comparison and analysis of bottom hole model, the bit pressure
301 fluctuation, torque and mechanical drilling speed during drilling, the rock breaking law PDC was
302 studied. The bit slowly drills down, completes the bottoming work of rock samples, starts the lower
303 turntable and applies bit pressure to make the bit drill normally (as shown in Fig. 16), starts the
304 dynamic test analysis system, and performs channel balance and zeroing, collects experimental data,
305 after reaching predetermined drilling depth, stops drilling and collects cutting. Each set of
306 experiments is repeated at least 3 times.



307
308 **Fig.16 Experiment process**

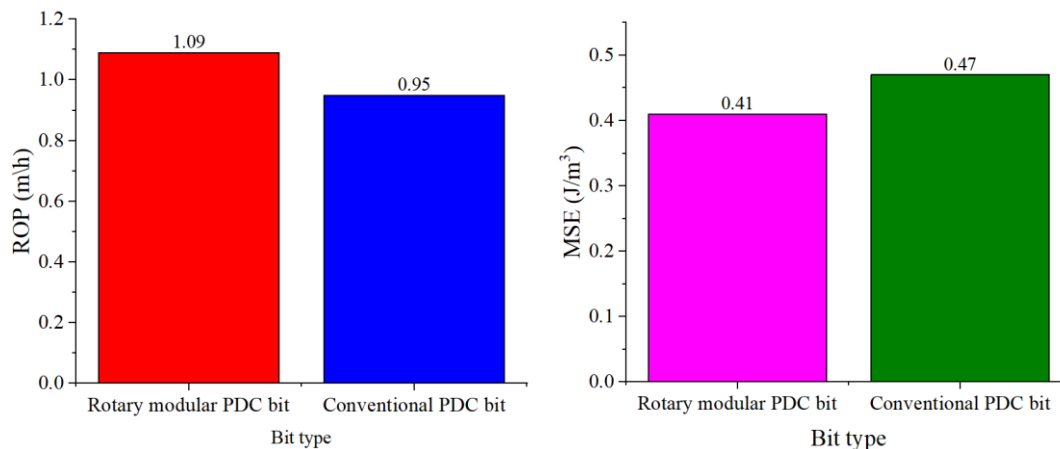
309 **4.3 Analysis of experimental results**

310 During the experiment, it is clearly observed that the module element rotates slowly at the
311 bottom of the well. The bottom of the well morphology obtained from the experiment is shown in
312 Fig.17. Because the relative height between the module element and the fixed cutting teeth in the
313 experimental bit is small, there is no local cross scraping track at the bottom of the well; however,
314 since the module element 5 is set at the hole diameter maintaining position of the bit, it can scrape
315 the well wall, in the red circle area in the figure There are traces formed after scraping the rotary
316 module, which also proves from the side that the rotary module element can rotate stably at the
317 bottom of the well, scraping the rock.



318
319 **Fig.17 Bottom hole morphology after the experiment**

320 The experimental bit controls the rotation of the rotating module element through the pin.
321 When the module element does not rotate, the experimental bit is a conventional PDC bit. When the
322 module rotates, the experimental bit is a new type of rotating module PDC bit. Fig. 18 is a
323 comparison ROP and MSE of two kinds of bits in sandstone when the WOB is 10kN and the rotating
324 speed is 10rpm. It can be seen from the chart that: compared with the conventional PDC bit, the
325 mechanical ROP of rotary modular PDC bit is 1.09m/h, which increases by 15%; the MSE is
326 0.41j/m³, which decreases by 14%. It shows that the rotary modular element can achieve local cross
327 scraping and reduce rock breaking energy consumption, Improve the rock breaking efficiency of the
328 bit.



329
330 **Fig. 18 Comparison of ROP and MSE of two kinds bits**

331 5. Conclusion

332 (1) A new type of PDC bit with rotating module can cool the cutting teeth, reduce the thermal
333 wear of the cutting teeth, and extend the life of the cutting teeth. At the same time, in the radial
334 coverage area of the rotating module element, there is local cross compound scraping, which can
335 improve the invasion ability of the cutting teeth and improve the rock breaking efficiency.

336 (2) Through the element experiment, it is known that the rotation speed of the rotating module
337 increases with the increase of the side angle, and decreases with the increase of the shaft angle; with
338 the increase of the shaft angle, the cutting load of the rotating module decreases first and then
339 increases, and with the increase of the side angle, the mechanical specific energy of the rotating

340 module increases gradually. When the journal angle is $10^{\circ} \sim 15^{\circ}$, the rock breaking energy
341 consumption of the rotating module element is higher. When the side angle is $10^{\circ} \sim 15^{\circ}$, the
342 rotation module element can realize stable low-speed rotation.

343 (3) Compared with the conventional PDC bit, the new rotary modular PDC bit has a 15%
344 increase in ROP and a 14% decrease in MSE.

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