CSCanada
Advances in Petroleum Exploration and Development
Vol. 17, No.1, 2019, pp. 79-84
DOI:10.3968/11131

ISSN 1925-542X [Print]
ISSN 1925-5438 [Online]
www.cscanada.net
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Development of the New Type Conical Teeth of PDC Drill Bit

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Received 15 October 2018; accepted 8 February 2019
Published online 22 April 2019

Abstract

The work elements of PDC drill bits are cylindrical polycrystalline diamond composite sheet and the cutting teeth of such shape can only cut the rock with the caster angle rake. In the process of drilling hard rocks, due to the large shear resistance and discontinuous cutting and rock breaking process, the rotation torque and torque ripple of drill bits are relatively large, resulting in low rock breaking efficiency and serious impact damage of composite sheet (Wilmot, 1998). In order to improve the ability of PDC drill bits to drill hard rock, a kind of cone PDC tooth is designed, which can plough and cut rocks with top rake, with low rock breaking resistance. It can reduce the rotation torque and torque ripple of drill bits, and improve the rock breaking efficiency and impact resistance of PDC drill bits.

Key words: PDC drill bit; Conical teeth; Plowing and cutting type; Rock breaking efficiency

Zhang, L. (2019). Development of the New Type Conical Teeth of PDC Drill Bit. *Advances in Petroleum Exploration and Development*, *17*(1), 79-84. Available from: http://www.cscanada.net/index.php/aped/article/view/11131
DOI: http://dx.doi.org/10.3968/11131

1. OPTIMUM CONE CROWN RADIUS

The smaller the cone crown radius of cone PDC teeth, the bigger the cone-apex angle and the thinner the insert crest. The thinner the tooth crest, the stronger the ability to penetrate into the stratum (Zou & Liang, 2004). However, if the tooth crest is too thin, it will be easily worn and broken. In order to determine the reasonable cone crown radius, five kinds of cone PDC teeth with cone crown radii of 1.0 mm, 1.5 mm, 2.0 mm, 2.5 mm and 3.0 mm were manufactured by using the material formula of polycrystalline diamond composite sheet, respectively.

1.1 Rock Breaking Force Experiment

Five kinds of cone PDC teeth with cone crown radii of 1.0 mm, 1.5 mm, 2.0 mm, 2.5 mm and 3.0 mm were used to cut rock samples at 14° cutting angle and the cutting depth of 1.0 mm, 1.5 mm, 2.0 mm, 2.5 mm and 3.0 mm, respectively, and the magnitude of tangential and vertical forces were monitored. The same experiment was carried out with a cutting angle of -15° with the φ16 composite sheet.

Table 1
Stress Test Results of Five Conical PDC Teeth With Different Crown Radii

Cone crown radius (mm)	Cutting angle (°)	Penetration depth (mm) 1.0		1.5		2.0		2.5		3.0	
		Axial force (kg)	Tangential force (kg)	Axial force (kg)	Tangential force (kg)	Axial force (kg)	Tangential force (kg)	Axial force (kg)	Tangential force (kg)	Axial force (kg)	Tangential force (kg)
1.0	15	137.24	31.63	162.41	38.29	187.34	43.25	214.23	54.67	247.50	72.58
1.5	15	153.40	39.26	192.27	45.53	217.56	51.37	273.16	60.46	321.09	87.30
2.0	15	170.23	44.58	205.47	50.51	250.62	57.22	312.43	79.20	354.06	108.25
2.5	15	195.17	47.30	232.37	56.24	327.36	64.25	357.68	92.36	412.53	115.37
3.0	15	213.50	53.21	284.96	60.54	397.04	73.23	437.08	100.43	507.43	125.14
Φ16mmPDC	-15	134.19	114.9	178.65	140.59	246.35	193.88	325.09	320.49	374.70	343.48

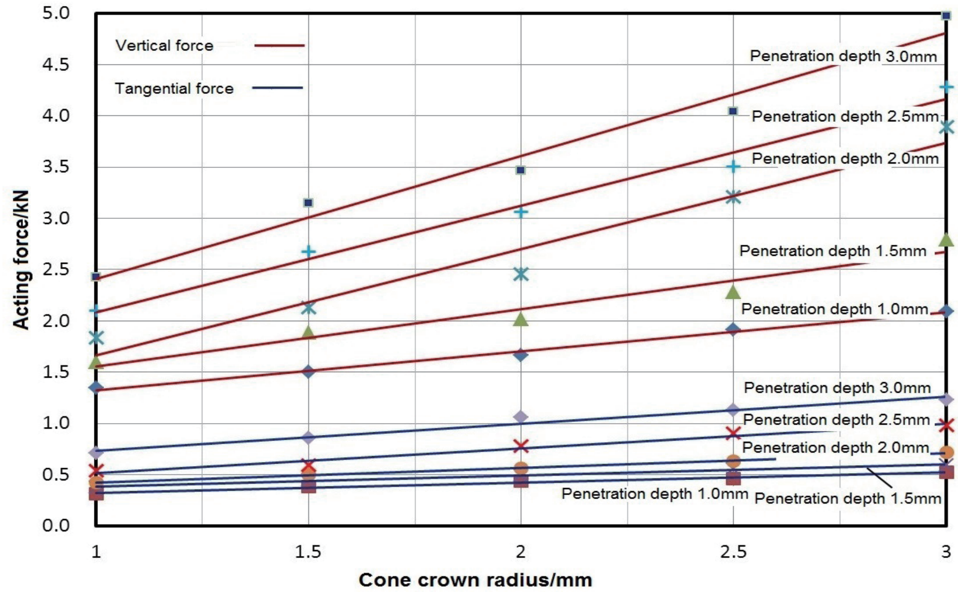

Figure 1
Variation rule of cone PDC tooth force with cone crown radius

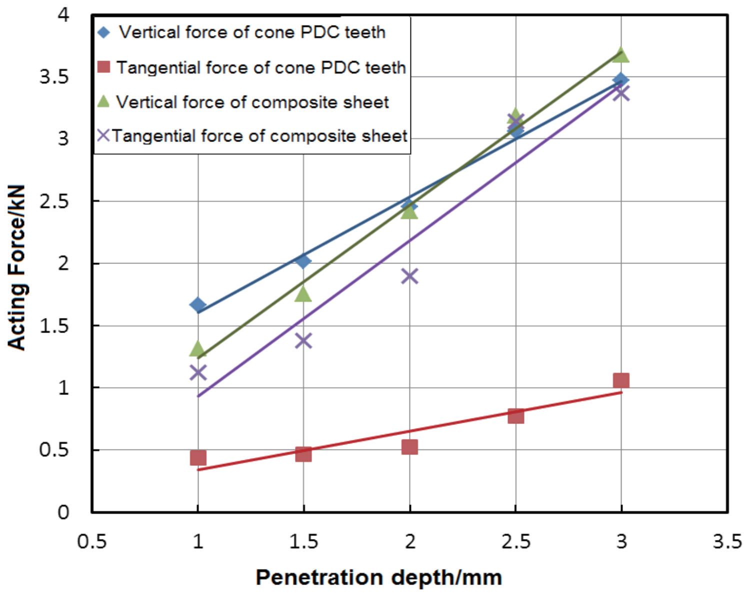

Figure 2
Comparison of force between cone PDC teeth and composite sheet

The results of rock breaking experiments showed that:

(1) The tangential force and the vertical force of the experimental cutting teeth have a proportional linear relation with the increase of the cone crown radius of the conical PDC cutting teeth. But the increase rate of vertical force is obviously greater than that of tangential force.

(2) The vertical force of the conical teeth is greater than that of the composite sheet when the penetration depth is shallow; and when the penetration depth arrives at one certain value, the vertical force of conical teeth is smaller than that of composite sheet.

(3) At the same penetration depth, the tangential force of cone PDC teeth is much smaller than that of composite sheet. The tangential force of the composite sheet is close to its vertical force, while the tangential force of the cone PDC teeth is about a quarter of its vertical force.

1.2 Abrasion Resistance Test of Cutting Teeth

The tested rocks are of extremely high hardness (granite) with the hardness of 7.2 (Moh's hardness) (Ohno & Karasawa, 2002). The test data are as follows:

(1) The penetration depth into the rock: 0.9mm;
(2) The rotational speed of cutting: 0.623m/s;
(3) The transverse velocity of lathe saddle: 0.545mm/s;
(4) Total length of cutting: 3,239m.

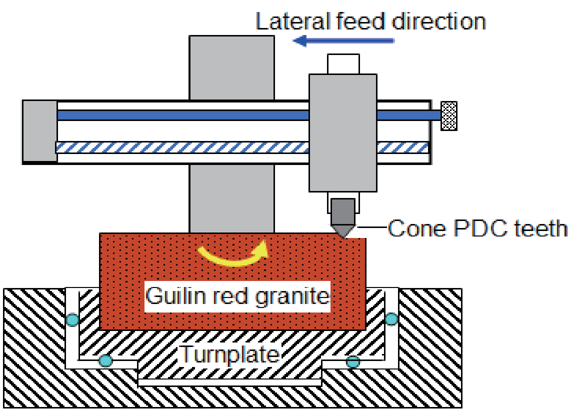

Figure 3
Schematic diagram of wear resistance test device

The cone PDC teeth with cone crown radii of 1.0, 1.5, 2.0, 2.5 and 3.0 mm were used to cut granite at the cutting angle of 15°, respectively. The depth of each cutting is 1.5 mm, and the cutting distance is 3,117 meters. The wear height of the teeth was measured.

The results of wear experiments showed that:

(1) The wear form of cone PDC teeth is normal abrasive wear without fragmentation and thermal damage;

(2) The rate of wear decreases with the increase of cone crown radius. But when the cone crown diameter exceeds 1.5mm, the rates of wear of the teeth with different cone crown radii are not very different.

Table 2
Wear Tests of Five Different Radii of Tapered PDC Teeth

Cone crown radius/mm	3.0	2.5	2.0	1.5	1.0
Worn height/mm	1.39	1.42	1.47	1.49	2.0
Rate of wear/mm/m	4.23×10-5	4.19×10-5	4.38×10-5	4.64×10-5	6.42×10-5

R=1.0mm R=1.5mm R=2.0mm R=2.5mm R=3.0mm

Figure 4
Wear patterns of tapered PDC teeth

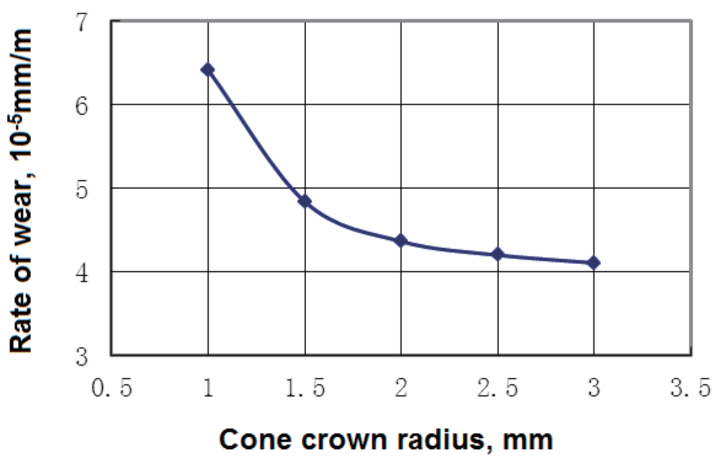

Figure 5
The variation of cone PDC tooth wear rate with cone crown radius

1.3 Impact Resistance Test

When PDC conical teeth cut the rock, they mainly bear two aspects of forces: one is the tangential impact load and the other is axial impact load. Through experiments, the overall performance (impact resistance) of this tooth shape is tested in an all-round way.

Test data of impact resistance of cutting teeth:
(1) Impact work: 11J;
(2) Impact frequency: 0.31 Hz
(3) Quality of drill hammer: 6kg;
(4) Dropping height of drill hammer: 0.25m;

Table 3
Impact Test on the Direction of PDC Conical Teeth

Cone crown diameter/mm	Impact times	Impact work/J	Observation results
1.0	80	800	No breakage, no crack
1.5	80	800	No breakage, no crack
2.0	80	800	No breakage, no crack
2.5	80	800	No breakage, no crack
3.0	80	800	No breakage, no crack

Table 4
Impact Test on the Direction of Shear Force of PDC Conical Teeth

Cone crown diameter/mm	Impact times	Impact work/J	Observation results
1.0	8	80	Fracture
1.5	16	160	Fracture
2.0	30	320	Fracture
2.5	32	350	Fracture
3.0	35	370	Fracture

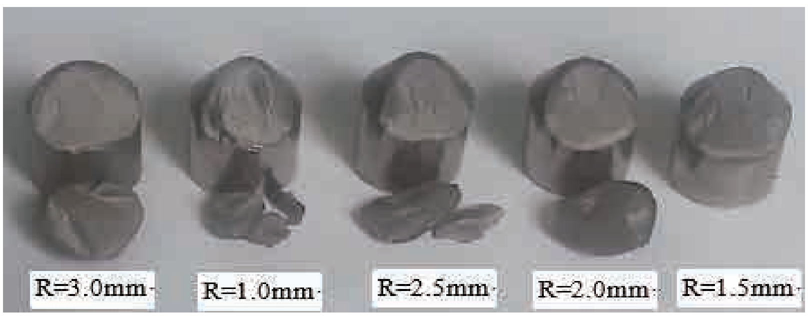

Figure 6
Tangential impact fracture of conical PDC teeth

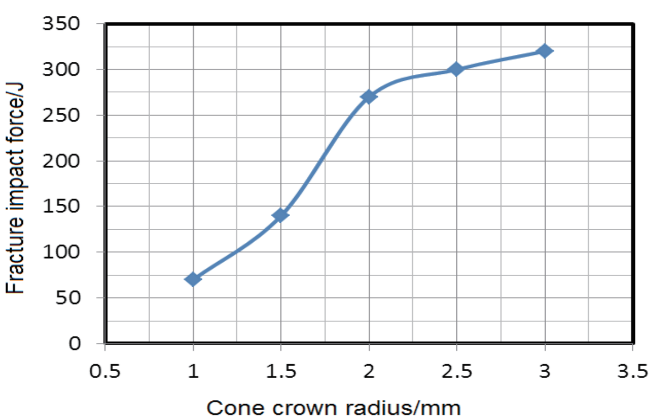

Figure 7
The influence of cone crown radius on impact resistance of tapered PDC teeth

The experimental results of impact resistance showed that:

(1) The axial impact resistance of cone PDC teeth is obviously higher than that of tangential impact resistance;

(2) The tangential impact fracture type of cone PDC teeth is brittle fracture of hard substrate;

(3) The tangential impact resistance of cone PDC teeth increases with the increase of cone crown radius. When the cone crown radius exceeds 2.0 mm, the increasing trend of fracture impact resistance work becomes slower.

2. CYLINDER DIAMETER AND CONE-APEX ANGLE DESIGN OF CONE PDC TEETH

To determine the reasonable diameter and cone-apex angle, five groups of cone PDC teeth with different sizes were designed. The cone-apex angles were 62°, 66°, 70°, 74° and 78°, respectively and the corresponding diameters of cone PDC teeth were 11.88 mm, 12.56 mm, 13.32 mm, 14.06 mm and 14.86 mm, respectively.

2.1 Calculation Results of Cone PDC Teeth

Table 5
The stress of cone PDC teeth of different sizes under load

	α =62° d=11.88mm	α =66° d=12.56mm	α =70° d=13.32mm	α =74° d=14.06mm	α =78° d=14.86mm
Minimum stress SMN/MPa	128	105	81.2	58.7	32.3
Maximum stress SMN/MPa	1550	1470	1320	1190	966

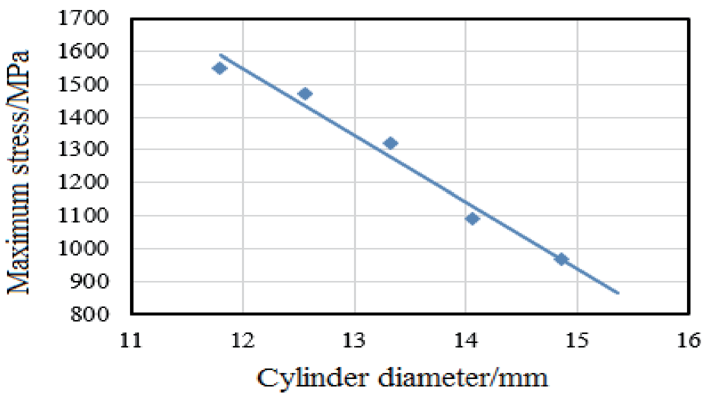

Figure 8
The relationship between the maximum stress and diameter of PDC conical teeth

The analysis of the stress status borne by the cone PDC teeth with different sizes showed that: with the increase of the diameter of cone PDC teeth, the maximum stress gradually decreases, and the strength of cone PDC teeth increases (Zou, *et al*., 2011).

2.2 Strength Check

σ[allow]>σMAX

σ[allow]=σ/γ

In the formula, σ[allow] - allowable stress, MPa;

σMAX - the maximum stress actually measured, MPa;

γ - safety coefficient, γ=1.3.

When the tensile strength of cone PDC teeth is 1,260 MPa, the allowable stress is:

σ[Allow] = σ/γ = 1,260/1.3 = 970 MPa

3. OPTIMUM MATERIAL FORMULA OF CONE PDC TEETH

The quality of cone PDC teeth directly affects the rock breaking efficiency and service life of drill bits. When the structure shape is fixed, the working performance of cone PDC teeth depends on their wear resistance and impact resistance (Eugene & Ray, 2012). Cone PDC teeth are composed of carbide substrate and polycrystalline diamond layer. Its wear resistance and impact resistance are determined by the wear resistance, thermal stability and fracture toughness of the polycrystalline diamond layer, the transverse fracture strength of the carbide substrate, and the bonding strength between the two layers.

3.1 Material Selection of Cemented Carbide Substrate

YG16 is generally used as cemented carbide substrate for polycrystalline diamond composite sheets. According to the results of impact test, the impact failure form of the cone PDC teeth with YG16 as substrate are mainly transverse fracture of cemented carbide substrate. This indicated that the transverse fracture strength of YG16 is relatively low (Sun & Ma, 2001). In order to improve the transverse fracture strength of cemented carbide substrate, YG20C cemented carbide with lower hardness (82.5HRA) and higher bending strength (25,000 MPa) was selected as the substrate material of cone PDC teeth.

3.2 Material Formula Design of Polycrystalline Diamond (PCD)

On the basis of data investigation and expert consultation, three formulas of polycrystalline diamond materials were designed. The mixture of the diamond micro-powder and cemented carbide substrate was compacted and assembled and placed in pyrophyllite synthesis die, which were sintered by cubic synthetic diamond press into the cone PDC teeth at pressure of 7.0GPa and temperature of 1,600℃.

Table 6
Formula Design of Polycrystalline Diamond

Formula number	Polycrystalline material	Substrate material
1	0.5-5.0um diamond 30%; 10.0-15.0um diamond 30%; 20.0-25.0um diamond 30%; cobalt powder 10%	YG20C
2	0.5-5.0um diamond 25%; 10.0-15.0um diamond 40%; 20.0-25.0um diamond 25%; cobalt powder 10%	YG20C
3	0.5-5.0um diamond 20%; 10.0-15.0um diamond 40%; 20.0-25.0um diamond 30%; cobalt powder 10%	YG20C

3.3 Wear Resistance and Impact Resistance Test

Table 7
The Results of Cone PDC Tooth Wear and Tangential Impact Test

Formula number	Rate of wear/ 10-5mm/m	Fracture strength	
		Impact times	Impact work/J
1	3.47	41	410
2	2.62	45	450
3	3.19	43	430

The wear resistance and tangential impact resistance of three kinds of conical PDC teeth were measured by wear test and impact test. It can be seen that formula 2 has good wear resistance and impact resistance.

CONCLUSION

(1) When the cone crown radius is 2.0 mm, the penetration ability, wear resistance and impact resistance of cone PDC teeth are higher;

(2) The optimization parameters of the structure of cone PDC teeth are cone-apex angle of 78°, tooth diameter of 14.86 mm and safety coefficient of 1.304.

(3) The conical tooth formula of 0.5-5.0um diamond of 25% + 10-15.0um diamond of 40% + 20.0-25.0um diamond of 25% + cobalt powder of 10% has good wear resistance and impact resistance.

(4) The cone PDC teeth products manufactured in laboratory have good properties with the rate of wear of 2.62 x 10^{-5}mm/m in granite, and the impact toughness of 450J. Its wear resistance and impact resistance are superior to those of domestic conventional PDC teeth (the rate of wear is 6.4 x 10^{-5} mm/m, and impact toughness is 350 J).

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