Indonesian Journal of Electrical Engineering and Computer Science
Vol. 1, No. 3, March 2016, pp. 627 ~ 634
DOI: 10.11591/ijeecs.v1.i3.pp627-634

Design Front Rake Angle of PDC Bit Based on Solid Works Simulation Method

Xiaoming Han*, Chenxu Luo, Xingyu Han
School of Mechanical and Power Engineering, Henan Polytechnic University
Jiaozuo 454000, China
e-mail: hanxmr@126.com

Abstract

In order to solve the bit front rake angle parameter selection problem of under different coal rock, it is proposed in polycrystalline diamond compact no core bit as the research object, and established a bit compact two-dimensional stress model of cutting teeth. The result shows that the front rake angle is the factor of cutting force and the drilling efficiency. Application of Solid Works simulation carries out the finite element simulation analysis respectively to different front rake angle of bit model under the conditions of soft rock and hard rock. Form the simulation results it can be concluded that under the condition of soft rock and hard rock, the optimal front rake angle is 10° and 15° respectively. It is obtained that the strength of the bit is largest and the life is longest on the best front rake angle of bit.

Keywords*: PDC; no core bit; finite element; optimal front rake angle*

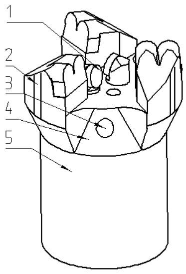
1. Introduction

For gas drainage drilling at mine, the bits mostly use Polycrystalline Diamond Compact (PDC) as the cutting teeth. Because the PDC has some advantages, such as hardness and abrasion resistance of diamond, structural strength and impact resistance of cemented carbide materials. It also can drilling quickly the coal and has the longer life under the low drilling pressure and high drilling speed. So, this kind of bits is widely used in coal mining and oil drilling [1-2]. In the drilling process, Wang et al [3] investigated the change of interaction between the cutting teeth and coal for the PDC by the finite element simulation method, and got the relationship between the working angle and broken coal volume from the results. Li et al [4] studied the change of crushing work ratio, when imposed static load and dynamic load at the surface of coal and inside the drilling hole, respectively, and obtained the interaction and the difference when crushing coal individually and jointly. Li et al [5] investigate the working mechanism of cutter edge of PDC, and pointed out that with the cutting coal depth become bigger, the drilling speed of bit increased. Through drilling experiments on different coal samples, Zhou et al [6-8] got the influence of the cutting parameters and coal protodyakonov coefficient on the stress of PDC, and the influence of teeth distribution parameter of cutter and cutter size on the drilling efficiency. However, the previous work focused mostly on the study of mechanism when PDC cutting teeth drilling coal rock, the reports on design of front rake angle is few. So, this paper established statics model of bit by the finite element simulation method, and for the bit of different front rake angle, investigated the change of stress-strain and displacement under the condition of soft coal rock and hard coal rock to get the corresponding optimal front rake angle.

2. Main Geometry Parameters of PDC

As a kind of whole bits, PDC bit is the most widely used bit. It is mostly used in the soft coal rock and hard coal rock. The appearance and structure of PDC are shown in figure 1. It is mainly made up of bit body, PDC, junk slot, radius retention, and nozzle and other components.

Received October 6, 2015; Revised February 22, 2016; Accepted February 29, 2016



1. PDC, 2. Radius retention, 3. Nozzle, 4. Junk slot, 5. bit body

Figure 1. Structure of PDC bit

PDC bit cutting teeth in spatial direction are determined by front rake angle α, assembly angle γ and side rake angle β, as shown in figure 2. Where, front rake angle α refers to the angle between cutting plane and the axis of the cutter of PDC; Assembly angle γ refers to the angle between the axis of the cutting teeth and the plane of the bit; Side rake angle β refers to the angle between cutting plane and bit radius plane [9]. The above three angles are determined by the structure of the PDC bit. The assembly angle is determined by the crown shape and the radial arrangement of the bit, and front rake angle α and side rake angle β are determined by the design of working angle of cutting tooth, especially closely related to the rationality of design of the front rake angle and the drilling efficiency.

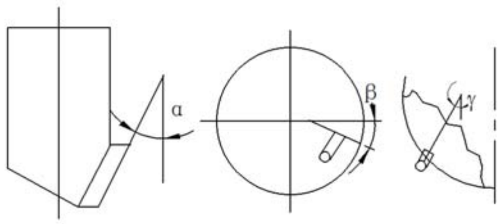


Figure 2. PDC bit direction of spatial structure parameters

Because there is a certain thickness of cutting teeth, when rotating in the cutting groove, The rear part will have friction and wear between the ring grooves and formation, and affect mechanical drilling speed, because the cutting edge is partly concentrated in the front part of PDC. In order to avoid the above situation, rotate the PDC in a certain angle along with the center line, so the side rake angle β is introduced. The friction and wear part of the rear supporting part of the cutting teeth between the rock and hole the rock layer is reduced. With the front rake angle increasing, the friction and wear part between the rock and hole the rock layer will be avoided. What's more, the side rake angle affects shape of bit blade, so it is often ignored in the actual design, and assumed to be zero.

3. Force Analysis of Bit Cutting Teeth

PDC bit under the drilling pressure, and shear coal under the action of torque. According to analysis of the process of cutting coal and rock when cutting teeth are under static pressure, we can obtain the calculating formula of the interaction force F_1 between the cutting teeth of bits and the coal rock [10]:

$$F_1 = \frac{Cbh \cos \phi}{\cos(\alpha + \psi + \theta + \phi) \cos \psi} \quad (1)$$

Where, C is cohesion of the coal rock; b is cutting teeth diameter; h is footage depth per turn of bit; θ is friction angle; ψ is angle between coal rock shear plane and bit cutting teeth feed direction; ϕ is friction angle inside the coal.

As can be seen from Eq(1), F_1 is ∞ or negative when $\alpha \geq \pi/2-(\psi+\theta+\phi)$, If the front rake angle is too large, The contact area between the cutting teeth of PDC and the coal rock become larger, and formed a strong extrusion to the coal, coal is unable to shear failure at this time, so its main failure modes are crushing. The compressive strength of coal rock is much larger than that of shear strength, so coal crushing need more bigger drilling pressure and tangential force, and the efficiency is very low. Therefore, the effective range of front rake angle is $0 \leq \alpha \leq \pi/2-(\psi+\theta+\phi)$.

When PDC cutting teeth is drilling the coal rock, besides the cutting force F_C and the drilling pressure W, it is also subject to the reaction of coal F_1, and there are also fraction F_3 and positive pressure P_2 at the interface of PDC cutting teeth and coal. as shown in figure 3.

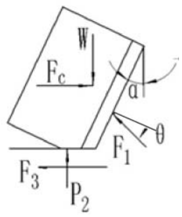


Figure 3. Cutting Teeth Stress Analysis

Friction coefficient between coal rock and wear surface is μ, so $F_3=\mu P_2$. According to Principle of force balance, we can get the following formula:

$$\begin{cases} W=F_1\sin(\theta+\alpha)+P_2 \\ F_c=F_1\cos(\theta+\alpha)+\mu P_2 \end{cases} \quad (2)$$

Where, The value of P_2 is related to the stress distribution on the wear surface.

$$P_2 = b\cdot p_m\cdot[\frac{0.6}{\cos\alpha}+\frac{1}{3}(\Delta L_f-\frac{0.6}{\cos\alpha})] \quad (3)$$

Where, ΔL_f is cutting teeth wear length; p_m is maximum value of coal rock stress. So $p_m = k\sigma_s$.
Submitting Eq(1) and Eq(3) to Eq(2), we can obtain the following formula:

$$\begin{cases} W=\frac{C\cdot b\cdot h\cdot\cos\phi}{\cos(\alpha+\psi+\theta+\phi)\cos\psi}\sin(\theta+\alpha)+b\cdot p_m\cdot[\frac{0.6}{\cos\alpha}+\frac{1}{3}(\Delta L_f-\frac{0.6}{\cos\alpha})] \\ F_c=\frac{C\cdot b\cdot h\cdot\cos\phi}{\cos(\alpha+\psi+\theta+\phi)\cos\psi}\cos(\theta+\alpha)+\mu\cdot b\cdot p_m\cdot[\frac{0.6}{\cos\alpha}+\frac{1}{3}(\Delta L_f-\frac{0.6}{\cos\alpha})] \end{cases} \quad (4)$$

As can be seen from Eq(4), The interaction force W and F_C of the PDC cutting teeth is related to the factors such as the cutting fore-angle α and the properties of the coal. Therefore, the cutting front rake angle α and the properties of the coal have a significant influence on cutting force and drilling efficiency of PDC. When the front rake angle becomes bigger, the three direction compressive stress of lower coal rock increases, which is uneasy to form shearing failure of bigger Volume. When the front rake angle becomes smaller, the rear part of the cutting teeth of PDC tends to be gentle, and cutting teeth cannot deeply feed coal rock. Therefore, the bit has the optimal front rake angle.

According to relevant literature, we can obtain coal property parameters and drilling parameters under different solid coefficients, as shown in table 1.

Table 1. Nature of Coal and Rock under Different Coefficient and Drilling Parameters

Coal property	C/mpa	θ/°	φ/°	ψ/°	μ/°	h/mm	ΔL_f/mm
Soft coal (f=1.5)	1.4	19	37	30	0.31	2	0.8
Hard coal (f=4)	6.2	23	34	30	0.40	1.1	1

Submitting above parameters to Eq(1) and Eq(4), we can obtain positive pressure and cutting force of bit cutting teeth when the solid coefficient of soft coal f is 1.5 and the solid coefficient of hard coal f is 4,as shown in table 2.

Table 2. Bit Cutting Teeth Stress under Different Coefficient

	f=1.5	f=4
F_1/N	496	1672
F_C/N	507	1681

4. Finite Element Simulation of PDC Bit

Some simplification was used to create the bit model with Solid Works software due to the little effect of bit surrounding radius retention strip, corner rounding and chamfer of bit strength.

(1) Ignore chamfer and radius retention strip characteristics of the model, which lead to uneven mesh easily.
(2) Ignoring the internal thread characteristics of the model, which has the little impact on the calculation results and easy to cause the grid division.

The actual size geometric modeling of the front rake angle composite bit of 0 °, 5°, 10°, 15°, 20°, 25° was builded. As shown in Figure 4.

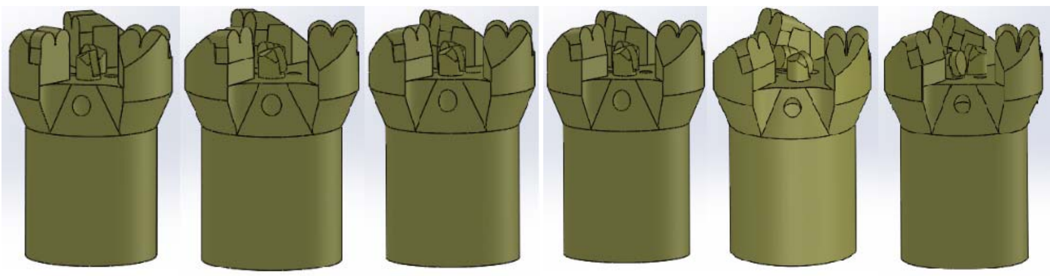


Figure 4. Different Tooth Fore-Angle Compact Drill Bit Model

The elastic modulus of polycrystalline diamond composite sheet of bit cutting teeth was setted to 790Gpa, Poisson than 0.07, the density of 2.9g/cm^3; bit body materials for the alloy steel, the elastic modulus of the material for the 210Gpa, Poisson than 0.25, with a density of 7.8g/ cm^3 in the Solid Works simulation software.

In the case of soft rock and hard rock, the value of the cutting force of the cutting teeth of different front rake angle is shown in Table 2. The full constraint was applied to the bottom surface of the bit, which can not be moved without elastic deformation. In this static model, the mesh parameters are set to the "minimum unit size".

5. Simulation Results and Analysis

5.1. Simulation Results Analysis in Soft Rock

Under the condition of soft rock, the stress and displacement images of different bits are obtained by static simulation of different front rake angle, in which the stress and displacement of the α=10° bit in soft rock are shown in Figure 5.

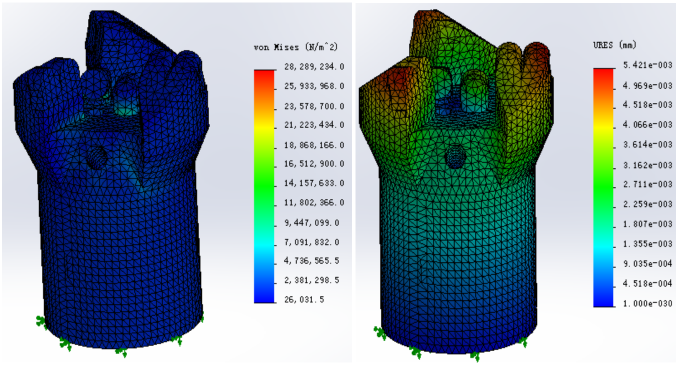


Figure 5. Bit Stress and Displacement Images under Soft Rock Properties

As can be seen from Figure 5, in the soft rock, the bit in cutting teeth position and the stress concentration suffer larger force, the bit suffering maximum stress is than 28mpa. Bit lateral cutting teeth deformation is biggest, and the biggest displacement change quantity is 5.4μm, which is in line with the actual drilling bit wear condition. According to the analysis, different front rake angle bit of maximum stress σ_{max} and maximum displacement u and the maximum strain ξ_{max} values is shown in Table 3 shows.

Table 3. Calculation Analyse Results of Different Tooth Fore-angle Bits

α/°	0	5	10	15	20	25
u/μm	9.1	6.3	5.4	6.9	9.3	13
σ_{max}/mpa	74	51	28	45	68	80
$\xi/10^{-4}$	2.2	1.7	0.9	1.4	2.4	2.9

The variation trend of the maximum displacement and the front rake angle of the bit in the soft rock condition is shown in Figure 6.

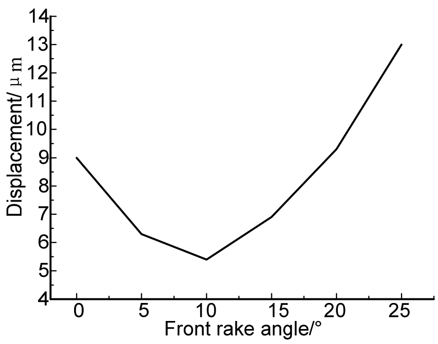


Figure 6. Displacement Change Trend of Different Front Rake Angle in Soft Rock

As can be seen from Table 3 and Figure 6, front rake angle bit from 0-10° interval of the stress decreases gradually, indicating that in this interval increasing front rake angle can reduce friction and wear, prolong the service life of the bit, enhance drilling efficiency; and in 10-25° interval the stress gradually increased, indicating that in this interval reduction front rake angle can increase the service life of the drill bit and improve drilling efficiency. In Table 3 and Figure 6 can be seen that the α=10° bit is the maximum stress force and displacement is the least, so the optimal front rake angle of bit drilling in soft rock is α=10°.

5.2 Analysis of Simulation Results in Hard Rock

Under the condition of hard rock, the stress and displacement images of different bits are obtained by static simulation of different front rake angle, in which the stress and displacement of the α=15° bit in hard rock are shown in Figure 7.

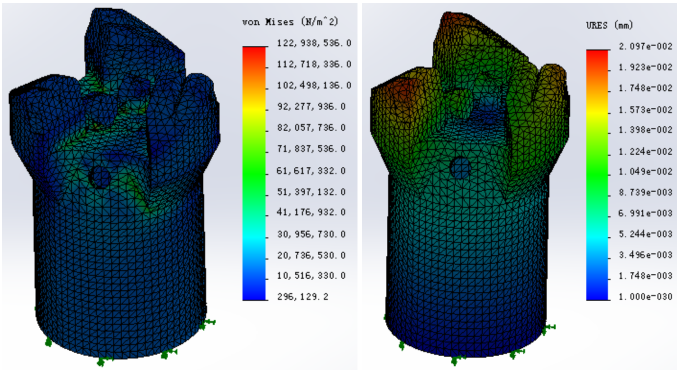


Figure 7. Bit Stress and Displacement Image under Hard Rock Properties

As can be seen from Figure 7, PDC bit in hard coal and rock under stress is larger than that in soft rock under stress, at this time, the bit subjected the maximum stress is 122mpa, the maximum displacement is 20.9μm. In drilling hard rock, because of the anti shear strength of the hard rock is far greater than the soft strength and hard rock of coal rock, drill for reaction is much larger than that of the soft rock drill for reaction, so the drilling in hard rock bit of the maximum stress is much larger than that of drilling in soft rock under the maximum stress. According to the analysis, different front rake angle bits of maximum stress σ_{max}, the large displacement u and the maximum strain ξ_{max} values are shown in table 4.

Table 4. Calculation Results of Different Front Rake Angle Bits

α/°	0	5	10	15	20	25
u/μm	56.6	39.3	25.9	20.9	28.2	41.6
σ_{max}/mpa	201	183	143	122	135	160
$\xi/10^{-4}$	6.9	6.4	5.7	3.7	4.5	5.2

The variation trend of the maximum displacement and the front rake angle of the bit in the hard rock case is shown in Figure 8.

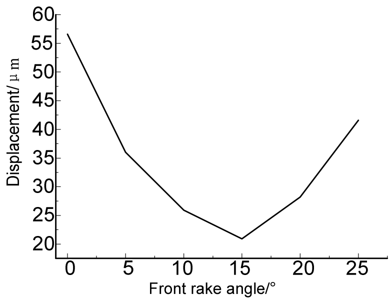


Figure 8. Displacement change trend of different front rake angle in hard rock properties

It can be obtained a conclusion from table 4: in the hard rock, the front rake angle between 0-15°, the biggest stress and displacement of the bit are gradually decreasing, indicating that in this interval increasing front rake angle can improve the service life of the bit, increase coal crushing efficiency; But in between 15-25° the maximum stress and displacement of bit increases, and the increase rate is bigger and bigger, indicating the reduction pinion angle is helpful to prolong the service life of the bit during this interval. When α = 15°, the biggest stress and displacement of bit change minimum. Therefore, the optimal front rake angle of the bit in drilling in the hard rock is α = 15°.

The reasons for the above phenomenon are the increase of the front rake angle the contact area of the composite and coal rock is increasing in the process of drilling hard rock when α=0-15°, the stress area of the cutting teeth is correspondingly larger, the bit is mainly to shear coal rock; with the increase of the front rake angle, the contact area between the cutting teeth and the coal rock is correspondingly larger when α=15-25°. But at this time the bit broken rock form is gradually transformed into broken crushing by shear crushing, and the compressive strength of coal rock is much larger than the shear strength, therefore, the maximum stress and displacement of the composite rock bit is changing gradually.

6. Conclusions

(1) The effective range of the front rake angle is $0 \le \alpha \le \pi/2-(\psi+\theta+\varphi)$ by the force analysis of the PDC bit's cutting teeth. The main factors affecting the cutting force and drilling efficiency is cutting teeth front rake angle.

(2) Using Simulation finite element simulation, the static analysis of different front rake angle bits in soft and hard rock is carried out. The results show that the optimal front rake angle of the bit in soft rock and hard rock is respectively α=10° and α=15°, and the strength of the bit is the largest and longest life when the bit is in the optimum tooth angle. It provides a reference method for the design of composite bit, and also provides a theoretical basis for the selection of PDC bit.

Acknowledgements

The authors are grateful for the funding of this work by the Henan province education department applied research project fund (15A440004, 16A460005) and Henan province science and technology project (162102210229).

References

[1] Liu Zhu-jian. The reasons of losing efficacy of PDC anchor bit and improving countermeasure. *Superhard Material Engineering*. 2012; 24(4): 28-32.
[2] Liu Xiang-dong, Qu Jun-li. Optimization Research on the Main Geometrical Parameters of PDC Anchor Bit. *Coal Mine Machinery*. 2010; 3(11): 29-31.
[3] Wang Zhen-quan, Zhou Yue-hui. Study on rock breaking regulation in optimizing cutting angle of PDC bit, *Coal Mine Machinery*. 2010; 30(8): 49-51.
[4] Li Guo-hua, Tao Xing-hua. Testing study on crushing work ratio of rock under dynamic and static load. *Chinese Journal of Rock Mechanics and Engineering*. 2004; 23(14): 2448-2454.

[5] Li Tian-jun, Yan Tai-ning, РК Богданов. Work mechanism of diamond compact cutting-edge. *Coal Geology & Exploration*. 2011; 39(2): 78-80.
[6] Zhou De-yong, CAI Huan. Experiment on effect of cutter parameters of PDC bit on rate of penetration. *Journal of China University of Petroleum (Edition of Natural Science)*. 2009; 33(5): 77-79.
[7] Zhou De-yong, Cao Ji-fei, Yuan Jun. et. Optimization design of the cutter size and back rake for pdc bit in hard formation. *Petroleum Drilling Techniques*. 2011; 39(6): 91-94.
[8] Zhou De-yong, Zhang Jiang-hai, WANG Rui-he. The experimental study of PDC bit mechanics model. *Petroleum Drilling Techniques*. 2005; 33(2): 41-43.
[9] Zhai Ying-hu, Cai Jing-lun, Liu Xi-sheng. Design of PDC bit cutter working angle. *Journal of China University of Petroleum (Edition of Natural Science)*. 1992; 16(1): 24-33.
[10] Zhao Fu-jun. *The oretical and experimental research on rock fragmentation under coupling dynamic and static loads*. Changsha: Central South University, school of resources and safety engineering. 2004.
[11] Guo Jian, Sun Wen-lei. The stress analysis of PDC drill bits in the process of drilling. *Machine Tool & Hydraulics*. 2008; 36(12): 25-28.
[12] Liang Zhong-yu, Ji Zhen-qiang, Chen Zhan-Qing, et al. Study on measuring experiment of coal mechanics performances. *Coal Engineering*. 2013; 10: 96-99.
[13] Wang Lai-gui, Zhang Peng, Yang Jian-lin, et al. Research on property modification and micro-mechanism of soft rock. *Bulletin of the Chinese ceramic society*. 2015; 34(1): 99-105.