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The Structure Design of Special-shaped PDC Reinforced-cutter and its Finite Element Method Analysis

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Abstract. A new structure is proposed to solve the failure mode of PDC cutter created by its mechanical fatigue, crack and diamond table delamination, so as to improve their service life. By applying the finite element method analysis, the force allocation of PDC cutter and multi-face (as known non-planar) designed PDC reinforced-cutter revealed that: the distribution and size of the internal stress in the cutter when working was improved, and the multi-face structure further reinforced the meshing force of the cutter's PDC layer and cemented carbide substrate. And thus significantly strengthen the shear-resistance capability. This is particularly meaningful to the kinematics of mono-cone bit and its adaptive exploration of rock-breaking features, as well as to the related scientific disciplines in the future.

Introduction

PDC cutter is made of polycrystalline diamond powder plus activator (Cobalt or Silicon) and cemented tungsten carbide (Wolfram Carbide, referred to as WC) substrate and sintered under high temperature and pressure. It owns key performance indicators including but not limited to wear resistance, high hardness, good thermal stability and impact toughness.

Since the initiation state of 1970s, the experimental stage of 1980s, the semi-experimental stage of 1990s and up to the current matured stages, the species gradually diversified and the application fields expanded. Starting from the 1980s, the PDC cutter is widely prevailed in the markets of measuring and cutting tools, down-hole tools of oil and gas drilling, mining and geothermal drilling industries.

During the recent two decades in the oil drilling project, thanks to numerous experts, scholars, corporate and field personnel, rapid development and innovation were compiled by means of their experience accumulated through theoretical design at home and abroad, indoor, and field test research. Here comes the PDC bit, and its usage beginning from the initial 10% to 30-50%, there are still an upward trend so far, mainly due to the development of Materials Science of the cutters.

(a) Mechanical fatigue failure (b) Crack failure (c) Delamination failure

Fig. 1 Photos of failure demonstration of PDC cutter

According to statistical data and on-site tracking record, the destruction of PDC bit in the early stage is owing to the of primary failure of PDC cutter, as shown in Fig. 1(a), (b), (c) below. The main form of failure can be divided in three types: (a) mechanical fatigue, (b) crack, and (c) the polycrystalline diamond table delamination) [2].

The failure come from two main reasons: (1) the PDC internal residual stress, mechanical fatigue, and temperature and etc., reduced the combination force between the crystal particles of material that lead to partial crack within the diamond polycrystalline table, or even a large area of the crack, and loss. (2) A PDC will start to have cracks around 700 deg C. As the cohesion between the mono diamond crystal will start to fail. At 1200 deg C, it is the mono crystal itself that start to graphitize.

For the failure mentioned above, all the solutions in the light of improvement on the distribution and magnitude of both internal stress and shear stress are limited [6].

Therefore, this article, in an over-all and in-depth analysis of the failure mechanism, proposed the multi-face (i.e., Multi-face) PDC strengthen cutter in the view of structure and relative process skill, will extend the service life of PDC bit, and bear important practical application meaning and far-reaching historical significance.

The structure design of multi-face PDC reinforced cutter.

The meshing plane constructed by the polycrystalline diamond layer (1) on the conventional cylindrical PDC cutter and the carbide (WC) substrate (2) was shown as Fig. 2.

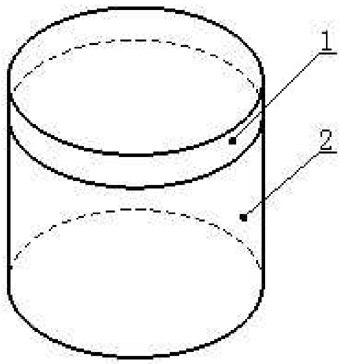


Fig.2 Conventional PDC cutter

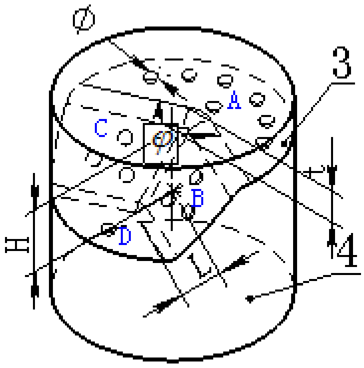


Fig.3 PDC reinforced-cutter's internal structure

The multi-face meshing constructed by the polycrystalline diamond body (3) of the multi-face PDC to strengthen cutter and cemented carbide substrate (4) was shown as Fig. 3.

Multi-face meshing structure means: the mating surface of the polycrystalline diamond body (3) and the cemented carbide substrate (4) are constituted by four different locations where each other is not on the same spatial space surface, that is *A-B-C-D* multi-face surface.

As shown in Fig. 3. Thickness from plane *A* to the surface of polycrystalline diamond cutter is *t*; plane *A* and *D* are parallel to the both sides(upper and lower) of the cylindrical cutter, its vertical distance is *H*; plane *B* and *C* formed to each other a "*V*" shape angle φ with oblique plane; plane *A-B-C* intersected in the center of cylindrical cutter, the plane *B-C-D* intersected at the cutting plane of the cylindrical cutter, the center distance is *L*, so that the plane *B-C* can be balanced with the cutting plane of the cylindrical cutter. Meanwhile, on the polycrystalline diamond plane *(A-B-C-D)*, a closed surface is designated where 14 hemisphere with diameter Φ corresponding to the ball pit of the cemented carbide substrate and weaved to each other.

The size of the cutter influents the rock suitability, stratum depth, and the inclination angle on the drill, it has to be designed based on actual working conditions. This structure mentioned in this paper is designed to change the impact of the external load on the cutter where its internal stress field distribution and size are concerned; thereby strengthen anti-destruction capability of the cutter, and further improve their cutting performance.

Analysis of Finite Element

Establish the mechanical model. The PDC bit breaks rock by means of shear. The PCD is the original cutting part which contacts direct with the rock (Fig.4). The depth of the strata during process is Δh; Cutter suffered by the load can be decomposed into a space vector, namely: the vertical loads opposites WOB direction is P_a; the tangential load and lateral load that opposite to the cutter movement direction of the cutter are P_t and P_h respectively; the sum of all the load projection is balanced with WOB.

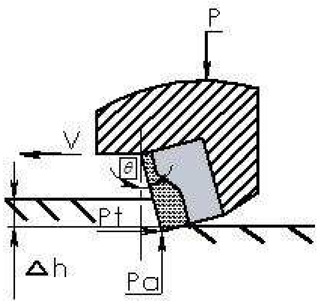


Fig.4 Multi-face PDC cutting

Fig.5 Solid model of Multi-face PDC cutter

According to the statistic in the field application, PDC bit in 8-1/2 inch hole is the most consumed type in oil field. This cutter's profile is cylinder and out diameter is 16mm.

As this size cutter example, the structural parameters: θ= 15 °; φ= 130 °; *H* = 5mm; *L* = 2.84mm, *t* = 2.5mm, Δh =2mm. The distance between the φ arc centerline of the multi-face messing surface and the PDC Shank axis is 2mm; θ is the anti-version angle on the PDC bits.

By using Solid Works to establish a mechanical model of the cutting cutter (shown in Fig. 5), import ANSYS Workbench, based on the actual condition of the PDC cutter, to conduct the static stress analysis on the structure;

To simplify the model, the impact of lateral load was neglected and the design and assumptions were structured as:

Conducted structure statics analysis to the PDC cutter, the factors, such as: temperature, time, speed, dynamic load and impact load, etc., are not taken into consideration;

The ante-version of the PDC cutter determines the cutting force into the strata, that is, the size of the cutting force is proportional to the ante-version angle. Therefore, the said angle is set as objective function to design of the structure;

The mesh of three-dimensional finite element was automatically divided by the software. This will make the PCD layer grid looks more intensive. The unit uses 8-node 6-Icosahedron, SOLID187 of solid elements, units totaled up to 285 641, the whole number of nodes is 420 312.

Material properties. The cutting element of the PDC cutter is polycrystalline diamond layer, the lower part is a WC matrix. The property of two materials defined as shown in Table 1[8]:

Table 1 Material properties

Material	Density ρ (kg/m^3)	Elasticity E (Mpa)	Boison Ratio μ	Tensile strength (Mpa)	Compressive strength (Mpa)
WC	15000	6.4e5	0.22	5.46e3	5.46e3
PCD	4100	8.0e5	0.08	7.40e3	7.40e3

Boundary conditions. The boundary conditions: the cemented carbide substrate of PDC cutter is embedded in the perforations on the drill bit body. Therefore, that part is set to a fixed constraint, as shown in Fig.6.

Load: Assumed the cut-in depth of PDC cutter into the rock is of 2mm, the load P = 30MPa, then establish Cartesian coordinates and cylindrical coordinates of the PDC cutter, the origin will be located at the center of composite surface. As long as the maximum stress of cutter, during breaking, is no more than the compression stress, the failure will not happen. The broken situation of cutter under static load can be analyzed through the internal stress and distribution at 30MPa. The loading matrix as follows:

$$[P_t \quad P_a \quad P_h] = P\begin{bmatrix} -\cos\theta & 0 & 0 \\ 0 & \sin\theta & 0 \\ 0 & 0 & 0 \end{bmatrix}. \tag{1}$$

$$[P_x \quad P_y \quad P_z] = \begin{bmatrix} -\sin\theta & 0 & 0 \\ 0 & \cos\theta & 0 \\ -\cos\theta & 0 & 0 \end{bmatrix}\begin{bmatrix} P_t \\ P_a \\ P_h \end{bmatrix}. \tag{2}$$

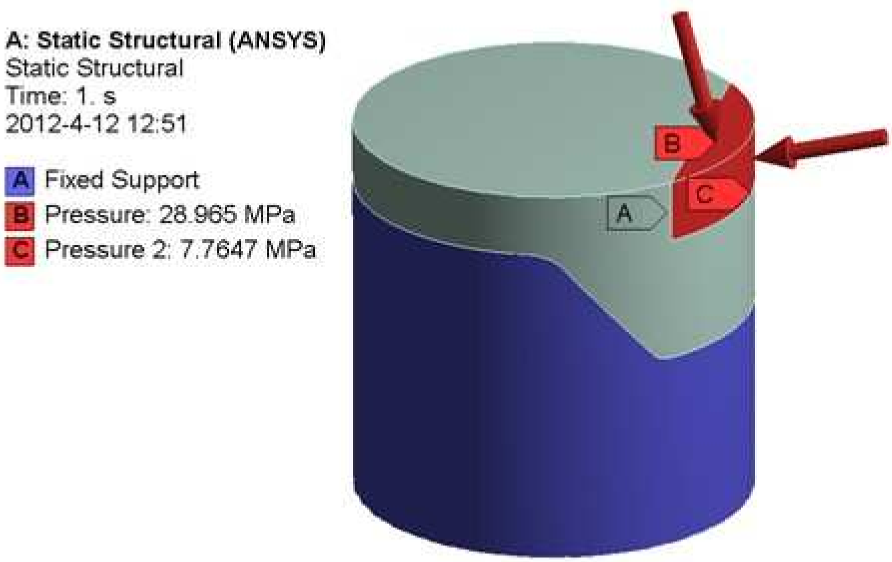
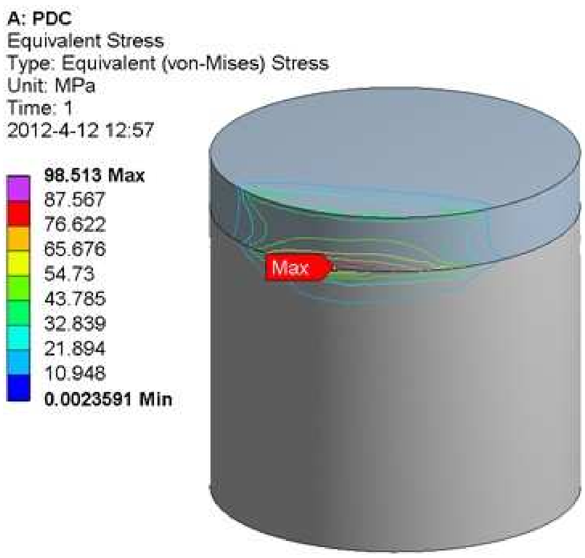


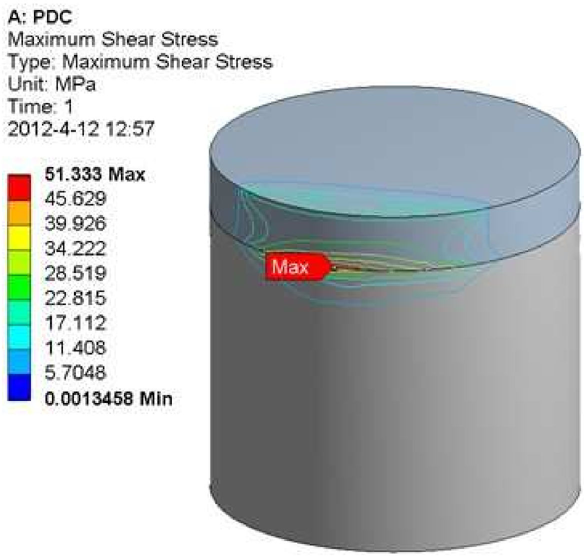
Fig. 6 Boundary conditions

Solution. Static analysis option is selected, and run the analysis software, you will get the stress and strain contour map. Linear static equation is $[K]\{x\}=[F]$.The direct solver is the inverse matrix $[K]^{-1}$ obtained by decomposing the coefficient matrix $[K]$, and got the result of $\{x\}=[K]^{-1}\{F\}\{x\}$.

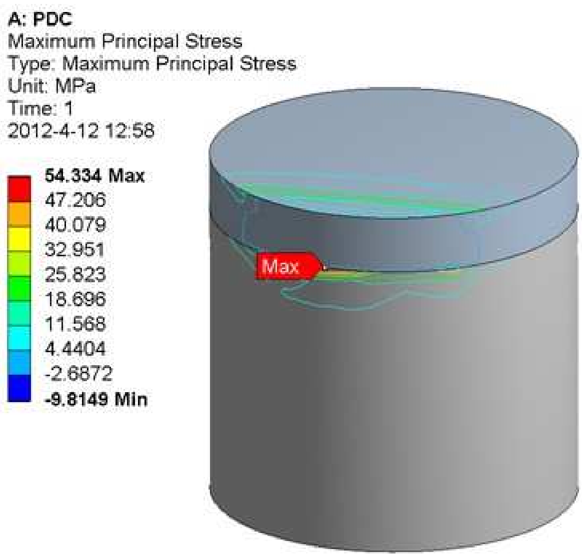
Strength theory analyze. By means of Von-Mises criteria and Tresca guidelines, the figures of material failure stress, the maximum shear stress and maximum principal stress were obtained as shown in Figure 7, 8. The principal vector stress after loading is shown in Fig. 7(d) and Fig. 8(d), where the maximum stress is in red, the minimum stress in green and the middle stress in blue. Based on these figures, the destruction situation of the cutter under static loading outlined as shown in Fig.11 where different stress were compared on two kinds of cutter.



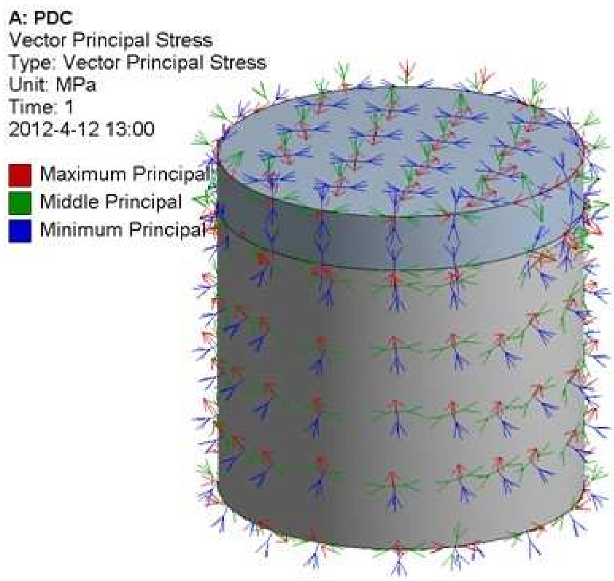
(a) Equivalent stress



(b) Maximum principal stress

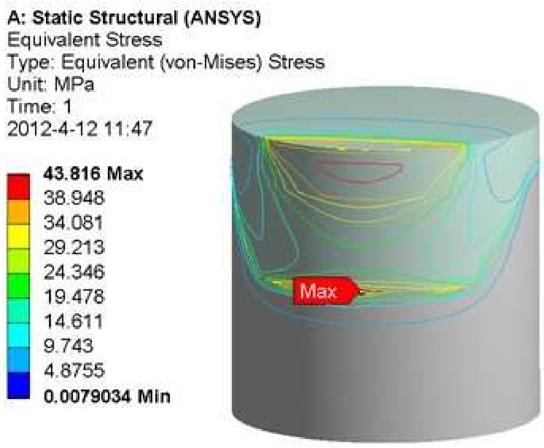


(c) Maximum shear stress

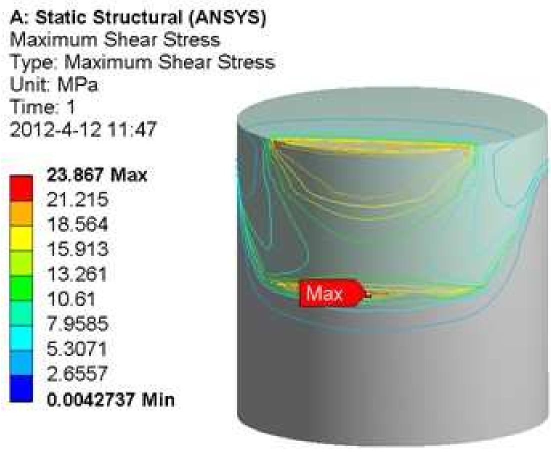


(d) Vector principal stress

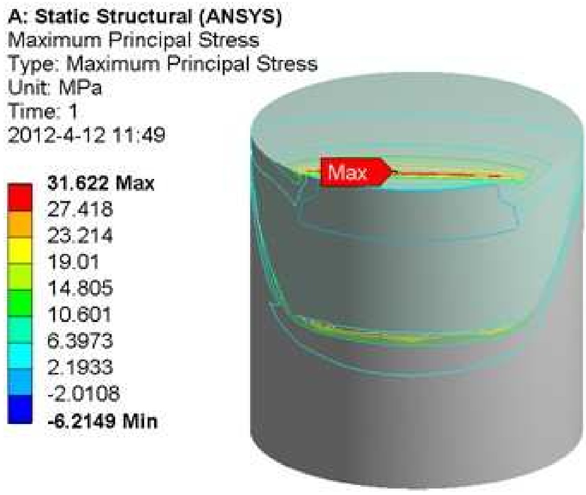
Fig.7 Conventional PDC cutter's stress isoline



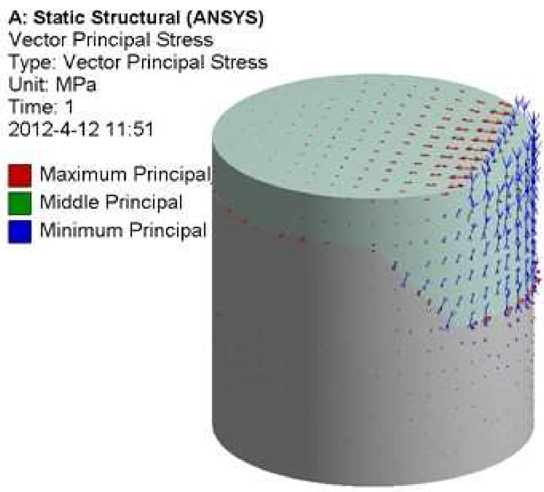
(a) Equivalent stress



(b) Maximum principal stress



(c) Maximum shear stress



(d) Vector principal stress

Fig.8 PDC reinforced-cutter's stress isoline

Result of analysis. Based on Fig.7, 8, it is clearly that: According to PDC cutter's equivalent stress as shown in Fig.7 (a), plus the principal vector stress as shown in Fig. 7 (d). We can arrive at the conclusion that among these vector stresses the maximum stress area is tensile stress (as shown in Fig.7 (d) in red). Because compressive strength of polycrystalline diamond material is about 6 times over that of tensile strength, so the mainly failure of PDC cutter was caused by tensile stress through the distribution of stress level. At the same time, the maximum equivalent stress of PDC cutter appeared near the joint surface of the composite layer. Therefore, the destruction of cutter is mainly beginning from the combination of surface area, polycrystalline diamond loses its back-up, and the destruction then gradually extended to the surface.

All the contact area is mounted by polycrystalline diamond material. The maximum Equivalent stress of the PDC reinforced cutter appeared on the surface of polycrystalline diamond, and gradually extended outward (Fig. 8). Under this situation, thecutter is mainly destroyed by fatigue wear.

The contrast line of two cutters is shown as Fig.9. The three sorts of stresses of PDC reinforced cutter, the equivalent stress, maximum shear stress and maximum principle stress, are far less than conventional one. It proved that multi-face structure can reduce the force acting and the internal stress distribution and size of the PDC reinforced cutter. Meanwhile, the integration of multi-face and meshing of the hemisphere with the ball pit did enhance the binding of the two materials which highly prevents the detachment of PDC layer from the cemented carbide substrate, thus extending their service life.

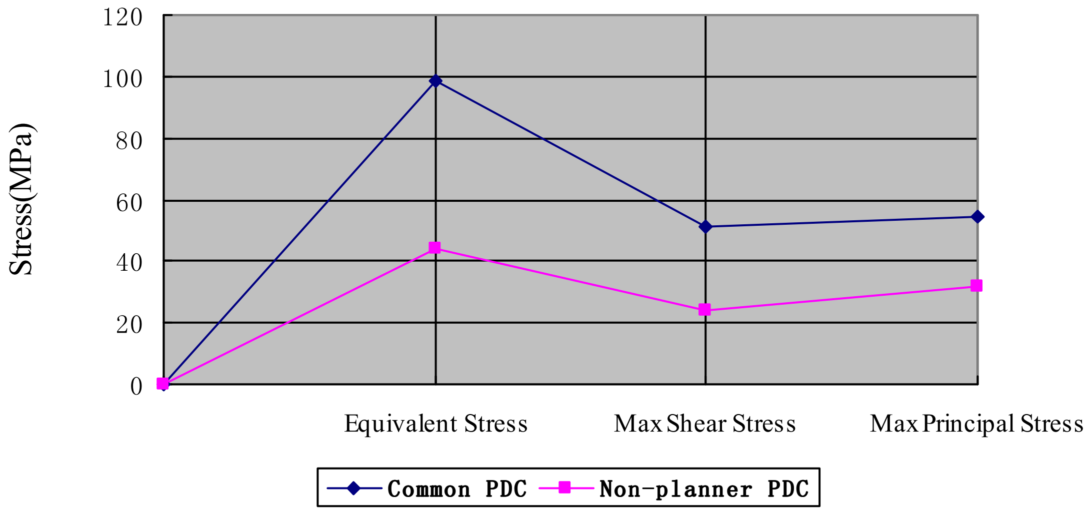


Fig.9 Comparison between two kinds of cutter under finite element analysis

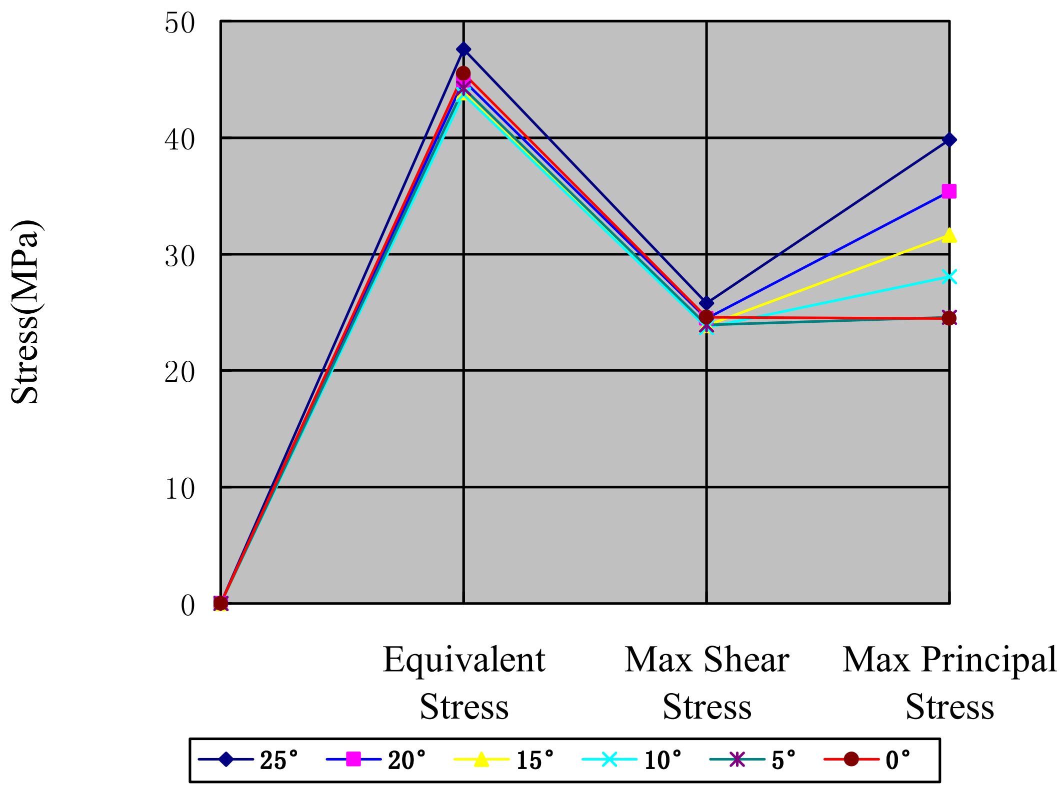


Fig.10 Cutting angle of the PDC reinforced-cutter

By using the anti-version angle θ as parameters, we can see per Fig.10:

The equivalent stress, maximum shear stress and maximum principal stress of PDC reinforced cutter will be increased in pace with the increment of cutting angel θ. Cutter's internal stress will increase obviously at θ≤5 degree equivalent to that of θ≥20 degree. Therefore, the angle of PDC reinforced cutter is suggested between 5 and 20 degree.

The equivalent stress, maximum shear stress and maximum principal stress are all increased stepping with the ante-version. The structure parameters of PDC reinforced-cutter maintained the following relationship: $f(\varphi, \phi, H, L, \Delta h) = \theta$.

Based on the above relationship, the size of cutter structure can be well adjusted to fit into actual working condition and achieved optimum cutting effect.

Conclusions and suggestions

The multi-face of PDC reinforced cutter will change the external load upon the shaped face that forms a 130 ° angle to each other. It will change the direction of force loaded on cutter, and uplift its high shear-resistance.

Applying the software of ANSYS Workbench, the force condition of general PDC and multi-face PDC cutters were respectively analyzed. It was proved the latter, after adapting multi-face structure design, will improve obviously the stress distribution and size of cutter, and reduce the probability of crake and detachment.

All the contact area is mounted by polycrystalline diamond material. Therefore, the wear resistance of the cutter can be reinforced during breaking rock. The features will lead to the exploration of cone bit that also is changing angel cutting.

This paper used structure static analysis method and conducted a primary study on the structure design and force condition of multi-face re-enforce PDC cutter. Therefore, the factors such as hole-down load, temperature, fluid, etc., are all not taken into consideration. The writer will maintain pertinent indoor experiment and in-site exercise to fulfill relative theory.

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