

# Rock cutting behavior of worn specially-shaped PDC cutter in crystalline rock

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**Abstract.** The specially-shaped Polycrystalline Diamond Compact (PDC) cutter is widely used in drill bit design due to its advantages of high rock cutting efficiency, strong impact resistance and long service life in hard and abrasive formation drilling. A detailed understanding of rock cutting behavior of worn specially-shaped PDC cutter is essential to improve the drilling efficiency and decrease the drilling costs. In this paper, the theoretical models of two new principles (loading performance (LP) and cutting performance (CP)) are derived for evaluating the cutting process of worn specially-shaped cutter, the theoretical models consider the factors, such as cutter geometry, aggressiveness, stress state, working life, and rock cutting efficiency. Besides, the numerical model of heterogeneous granite is developed using finite element method combined with Voronoi tessellation, the LP and CP of 12 kinds of worn specially-shaped PDC (SPDC) cutters are analyzed. The results found that the mechanical specific energy (MSE) of worn cutters first increase and then decrease with increasing the cutting depth, and the MSE increase with the increase of back rake angle except for Conical cutter and Wedge-shaped cutter. From the perspective of CP, the worn PDC cutters are more suitable for the smaller cutting depths, and the back rake angle has little effect on the CP of the specially-shaped worn PDC cutters. Conical cutter, Saddle-shaped cutter and Ellipse-shaped cutter have the highest CP value, while Rhombus-shaped cutter, Convex cutter and Wedge-shaped cutter have the lowest value in selecting cutters. This research leads to an enhanced understanding of rock-breaking mechanisms of worn SPDC cutters, and provides the basis to select of specially-shaped PDC cutters for the specific target formation.

**Keywords:** cutter selection efficiency; cutting performance; granite; loading performance; specially-shaped PDC cutters; wear

## 1. Introduction

The cutter wear is the key factor affecting the rock breaking efficiency of drill bit and drill cost, especially in deep and ultra-deep formation (Warren and Oster 1999, Zhang *et al.* 2015, Zhu and Liu 2017). In drilling process, the cutter temperature increase sharply due to its high strength extrusion friction with rock, which will aggravate the cutter wear, cause the failure of cutter eventually. In strong abrasive formations, like Xujiahe formation in Sichuan province of China, the rock is extremely abrasive and contains a large amount of siliceous cemented quartz sandstone, resulting in the extremely short life and high consumption of drill bit (about 73.3% of the drill bits used in a well). The Xujiahe section is less than 40% of the completed well section, but the drilling cycle accounts for 80% of the total well, which greatly increases the drilling cost (Hu *et al.* 2013, Zhuang 2011). It is, therefore, of great significance to explore the cutting performance of PDC cutters after wear for improving the rock breaking efficiency of drill bit and reducing drilling cost.

PDC cutters are widely used because of its high rate of penetration (ROP), long service life and good self-

sharpening (Xiong *et al.* 2020, Dai *et al.* 2020). However, conventional planar PDC cutters are not suitable for the hard and highly abrasive rock (Yang *et al.* 2009, Zhang 2014). Therefore, more specially-shaped cutter (SSC) with different cutter surface structures have also been introduced into rock cutting and achieved good performance (Lin 2019). Compared with conventional planar PDC cutters, Conical PDC cutters (“Stinger” cutters) have lower cutting force, strong impact resistance and wear resistance (Zou *et al.* 2015, Xiong *et al.* 2020); Axe PDC cutters require less cutting force in hard granite cutting and make the rock is more easily broken (Crane *et al.* 2017); the Tri-planar PDC cutters are easier to penetrate into the rock, and has higher rock breaking efficiency in the highly abrasive and strong impact formation (Liu *et al.* 2021); Concave PDC cutters with shallow concave characteristics can effectively reduce the cutting heat on cutter during cutting (DiGiovanni *et al.* 2014). Cutter’s wear is the main reason for the failure of drill bits (Appl *et al.* 1993, Tze-Pin *et al.* 1992). According to laboratory test results, non-planar PDC cutters are more wear-resistant than planar PDC cutters (Crane *et al.* 2017, Tulu *et al.* 2008, Tulu *et al.* 2009, Richard *et al.* 2010), but the extreme stress caused in cutter when penetrate into the hard and abrasive rock also makes the cutter wear (Glowka *et al.* 1985, Glowka *et al.* 1986). Wear is the process by which the bit life and rock breaking efficiency are reduced due to the removal of cutter material (Michaels *et al.* 2019), it is characterized by the blunt edge of cutter, and the size of

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the blunt increases with time and eventually develops into a large wear plane (Rostamsowlat *et al.* 2022). The wear of cutter can be divided into thermal wear and mechanical wear (Li 2016). Thermal wear is mainly manifested as the wear rate of cutter will gradually rise as the cutter temperature increases to a threshold value, and the wear rate will not remain constant even if the cutter temperature remains constant (Appl *et al.* 1993). The worn surface will be more damaged at a higher temperature. It is generally believed that the PDC cutter wear will be affected when the temperature exceeds 350°C (Glowka *et al.* 1985). Mechanical wear is represented by four main wear modes: abrasive wear, micro-chips, macro-chips and delamination (Michaels *et al.* 2019). Under normal abrasive wear conditions, PDC cutters will produce significant wear planes before reaching half of their service life. Therefore, PDC drill bits should be designed to operate effectively under wear conditions (Glowka 1985).

The cutter wear development can change the mechanical response of PDC bits and reduce their rock breaking efficiency (Geoffroy *et al.* 1998), it is essential to make accurate prediction of bit wear in the complex downhole working condition. The corresponding analytical models or real-time data analysis are usually used alone to predict bit wear (Mohamed *et al.* 2011, Rashidi *et al.* 2010), but this still leaves much to be desired. So many researchers have proposed several new prediction models, like the analytical models that combine real-time gamma-ray data to predict PDC wear, which can be used to estimate bit wear during the drill run schedule even if the drilling pressure and speed are not known (Liu *et al.* 2014); or the analytical models that includes all drilling parameters including rock-drill interaction, bit profile, rock strength and bit hydraulic structure can be used to assess the wear the wear of cutters on the inner and outer cone of the bit (Mazen *et al.* 2020). Models that combine the concepts of rock energy and drilling strength (Rashidi *et al.* 2008) and models that exploit the effect of real-time downhole dynamics on drilling parameters and use self-response data analysis allow for real-time prediction of bit wear (Lakhanpal *et al.* 2017).

At present, researches on PDC cutter wear mainly focus on its wear mechanism or bit wear prediction, but few researches pay attention to the rock cutting mechanism of worn cutter. In this paper, the theoretical models of two new principles of loading performance (LP) and cutting performance (CP) are established for evaluating the cutting process of worn SSC, the models consider the factors, such as cutter geometry, aggressiveness, stress state, working life, and rock cutting efficiency. The numerical model of heterogeneous granite is developed using finite element method combined with Voronoi tessellation, and the LP and CP of 12 kinds of worn specially-shaped PDC cutters are analyzed. The results of the study have a non-negligible impact on extending the service life of PDC cutters and improving the use efficiency of PDC cutters.

## 2. Evaluation of worn SSC in granite cutting

### 2.1 Rock breaking efficiency

There are many models for evaluating the rock breaking efficiency, but the most commonly used model is the MSE proposed by Teale in 1956 (Teale 1965), which define the MSE as the energy consumed to remove a unit volume of rock, i.e.

$$MSE = \frac{W}{V} \quad (1)$$

where  $MSE$  is the mechanical specific energy (MPa);  $W$  presents the total work consumed by removing the rock (J);  $V$  is total volume of the removed rock ( $\text{mm}^3$ ). From Eq. (1), it can be seen that the smaller the  $MSE$ , the higher the rock cutting efficiency.

According to Evans' dense nucleation theory, a dense core will be formed beneath the indenter when the indenter penetrates into the rock, and a plastic deformation zone will be formed under the dense core subsequently (Evans 1962). Related researches indicate that the tool also satisfies the relevant laws of the dense kernel theory during cutting (Liu *et al.* 2002). Therefore, As shown in Fig. 1, the fragmented rock in rock cutting consists of three parts, the rock chips directly removed by cutting above the cutting depth (called the removal zone), the extrusion area of rock by PDC cutter (called the dense nucleus), and the plastic deformation area beneath the dense nucleus (Zhu *et al.* 2020). The dense core and plastic deformation zone are regard as the damaged zone, the damage degree of the rock at damaged zone will affect the breaking efficiency in subsequent rock cutting. Therefore, the MSE of each cutter in this study is determined by the following method,

$$MSE = \frac{W}{V_t} = \frac{E}{V_p + V_e} \quad (2)$$

where:  $V_t$  - equivalent crushing volume considering the effect of plastic rock crushing ( $\text{mm}^3$ );  $E$  - energy consumed by crushing rock (J);  $V_e$  - volume of rock debris in the forced removal zone ( $\text{mm}^3$ );  $V_p$  - equivalent volume of rock debris in the damaged zone ( $\text{mm}^3$ ).

### 2.2 Load performance of SSC

Another important indicator of rock cutting is the cutting force, which directly affects the cutter life as well as the drill bit life. At the same time, the cutter life is also related to its geometry. Generally, the larger the cutting force, the more easier it will be worn, and the more

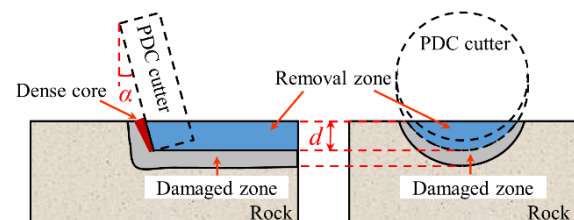


Fig. 1 Cutting diagram of PDC cutter

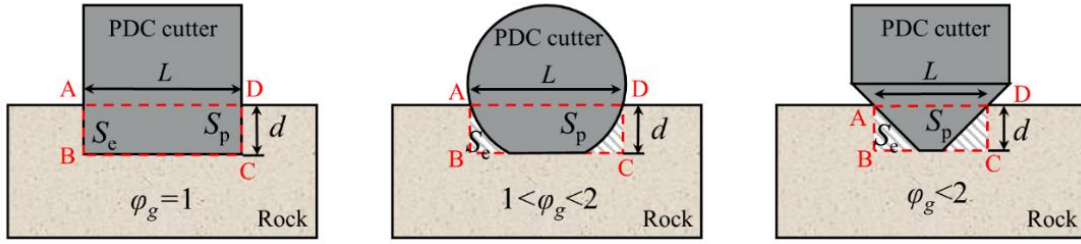


Fig. 2 Relative position of worn SSC to the rock and geometric sharpness of cutter

concentrated the force on the cutter, the more likely it is to be damaged, and with shorter life. Therefore, the study of the force condition of specially-shaped PDC cutter can help to measure the cutter life more accurately. Here, the LP of SSC is defined as an index which considering the geometry, aggression performance and stress distribution of cutter in rock cutting. The following is the detailed analysis of the LP of SSC from these three perspectives.

With regard to the geometry of the SSC, the sharpness of the cutter determines the stress state and rock cutting efficiency of cutter to some extent. The sharpness of the cutter can be considered as the resistance of cutting when penetrating into rock, the smaller the penetration force, the sharper the cutter, on the contrary, the more blunt of the cutter. The sharpness of cutter not only governed by the cutter geometry, but also related to the cutting parameters such as cutting depth and back rake angle of cutter and so on. Fig. 2 shows the projection of three typical shapes of worn SSC cutters along the cutting direction. In the Figure,  $S_p$  is the projected area of the SSC cutter along the cutting direction,  $S_e$  is the area of the rectangle ABCD, which the length is the contact edge of cutter and the free surface of rock and the height is the cutting depth.

As can be seen from Fig. 2, the difficulty of rock indentation decreases from Fig. 2(a) to 2(c) under the same cutting depth and external load, which means the sharpness of these three shapes of cutters increases gradually. The geometric sharpness  $\varphi_g$  is introduced to measure the effect of geometry and rock cutting parameters on the cutter sharpness, it is defined as the ratio of the projected area of cutter to the blunted area, i.e.

$$\varphi_g = \frac{S_e}{S_p} = \frac{Ld}{S_p} \quad (3)$$

where the  $\varphi_g$  is the geometric sharpness of PDC cutters, dimensionless;  $S_e$  is the blunted area ( $\text{mm}^2$ );  $S_p$  is the projected area of PDC cutter ( $\text{mm}^2$ );  $L$  is the contact length between PDC cutters and rock (mm);  $d$  is the cutting depth (mm).

The geometric sharpness  $\varphi_g$  can dynamically characterize the relative sharpness of SSC under different cutting parameters, the larger the value of  $\varphi_g$ , the "sharper" the cutter is. Moreover, it can be seen from Fig. 2 that the value of geometric sharpness  $\varphi_g$  is a constant between 1 and 2 when the cutter profile and cutting parameters are fixed. When  $\varphi_g = 1$ , the projected area of cutter overlaps with the blunted area, and the force on the cutter is relatively large

under the same cutting parameters. when  $\varphi_g = 2$ , the projected area of PDC cutter is a triangle with the vertex facing downward (i.e., the PDC cutter is an unworn conical cutter), and its area is just half of the blunted area, and the force on the cutter is relatively small.

In terms of SSC aggressiveness, in order to improve the life of the PDC cutters while increasing the rock-breaking efficiency to a greater extent, the most ideal situation is that the stress on the cutter is minimized while the stress generated on the rock is maximized. In this way, the probability of cutter damage is smaller, and therefore its service life is relatively longer. To characterize this property of cutter in rock cutting, another variable is defined, the cutting sharpness  $\varphi_c$  of PDC cutter, which is calculated by the formula

$$\varphi_c = \frac{\langle \sigma_{\max}^R \rangle}{F} \quad (4)$$

where the  $\varphi_c$  is the cutting sharpness of PDC cutter ( $\text{mm}^{-2}$ );  $\langle \sigma_{\max}^R \rangle$  is the average value of the maximum Mises equivalent stress of rock (MPa).  $F$  is the average value of the cutting force (N).

The larger the value of  $\varphi_c$ , the stronger the aggression performance of the SSC, conversely, the weaker the aggression performance. To compare the aggression performance of different SSC under different cutting parameters, the geometric factors of PDC cutter are taken into consideration. The aggression degree (integrated sharpness)  $\varphi$  of PDC cutter is introduced and defined as the product of cutting sharpness  $\varphi_c$  and geometric sharpness  $\varphi_g$ , i.e.,

$$\varphi = \varphi_c \varphi_g = \frac{\langle \sigma_{\max}^R \rangle S_e}{FS_p} \quad (5)$$

where the  $\varphi$  is the aggression degree of PDC cutter ( $\text{mm}^{-2}$ ).

In addition, the service life of PDC cutter is not only related to the cutting force, but also related to the stress distribution on cutter. Generally, the cutter first damages at the place where the stress is concentrated. Therefore, To characterize the stress distribution of PDC cutter during cutting, the stress concentration coefficient  $\xi$  is introduced and its expression is defined as

$$\xi = \frac{S^*}{S_p} \quad (6)$$

where the  $\zeta$  is the stress concentration coefficient, dimensionless;  $S^*$  is the equivalent projected area on the PDC cutter at the location where the maximum stress in the rock occurs during the cutting ( $\text{mm}^2$ );  $S_p$  is the projected area of the PDC cutter ( $\text{mm}^2$ ).

From the above definition, it can be known that the stress concentration coefficient is a constant less than 1, which expresses the stress state of the PDC cutter. The larger value of  $\zeta$  means the more uniform of the stress distribution on cutter under a certain cutting parameter, it is less likely to be damaged; in contrast, the smaller  $\zeta$  indicates the stress distribution is more concentrated and the cutter is more easily damaged.

It is easy known that the larger of geometric sharpness and aggressiveness, and the more uniform the stress distribution, present the better the LP of SSC. Therefore, the LP of SSC can be expressed as the product of aggressiveness and stress concentration coefficient, i.e.

$$\eta = \varphi \zeta = \varphi_c \varphi_g \zeta = \frac{\langle \sigma_{\max}^R \rangle}{F} \cdot \frac{S_e}{S_p} \cdot \frac{S^*}{S_p} = \frac{\langle \sigma_{\max}^R \rangle S_e S^*}{F S_p^2} \quad (7)$$

where the  $\eta$  is the LP coefficient of SSC ( $\text{mm}^{-2}$ ).

The LP coefficient  $\eta$  of the SSC considers the aggressiveness and stress distribution of cutter. The larger value of  $\eta$  infers the specially-shaped PDC cutter can achieve its own approved rock-breaking aggressiveness and improve its own force state at the same time under the cutting parameters. Therefore, the life time of this specially-shaped PDC cutter can be well guaranteed.

### 2.3 Cutting performance of SSC

As mentioned above, it is difficult to balance the rock breaking efficiency of drill bit and its service life during drilling. When selecting the cutter shape and rock cutting parameters, the rock-breaking efficiency should not be considered simply, but also the LP should be considered comprehensively to achieve a balance between service life and rock-breaking efficiency of drill bit. Therefore, the rock breaking efficiency and LP of the SSC are collectively referred to as its cutting performance (CP) to evaluate the CP of cutter, and the cutting performance coefficient  $\lambda$  is introduced to measure the value of CP and it is defined as

$$\lambda = \frac{\eta}{MSE} \quad (8)$$

where  $\eta$  is the loading performance coefficient of SSC ( $\text{mm}^{-2}$ );  $MSE$  is the mechanical specific energy of SSC (MPa);  $\lambda$  is the cutting performance coefficient of SSC ( $\text{N}^{-1}$ ).

The above analysis shows that the CP coefficient  $\lambda$  takes into account the rock breaking efficiency, geometry and stress distribution of PDC cutter, and can fully reflect the difference of energy consumption, service life and aggression performance of each SSC. It can provide guidance for designing the PDC drill bit and the selecting the cutter shape and cutting parameters by comparing the value of CP coefficient  $\lambda$  of each SSC under the same cutting parameters.

## 3. Rock cutting model of worn SSC

### 3.1 Finite element model of heterogeneity granite

A numerical simulation model of heterogeneity granite is developed based on the finite element method. The heterogeneity of granite is realized by the Voronoi subdivision algorithm, the core of the method is to assign different material properties according to the relative spatial position of the unit and the mineral bin. The specific modeling and calibration method can be referred to our previous study (Zhu *et al.* 2021). The general process is as follows, according to the mineral fractions inside the granite X diffraction experiment and CT scan experiment, combined with the granite specimen size in the numerical simulation experiment, randomly distributed and sized spheres (called mineral seeds) are generated in a specific spatial range, and the corresponding mineral properties are assigned to them. The mineral component and the percentage of granite are reflected by the size of the mineral seeds and the percentage of their fraction. Subsequently, a specific space (which is generally set to be slightly larger than the size of the heterogeneity part of the granite specimen) is divided into Voronoi polyhedron according to the spherical center coordinates of the mineral seeds, and each sub-Voronoi polyhedron (called mineral bin) inherits the original specific mineral properties.

Finally, the granite component is created and meshed, and the corresponding mineral material properties were assigned to the mesh cells according to the spatial location of each mesh cell in relation to the location of the mineral bin. If all nodes of the grid cell are located in the same mineral bin, the material of the cell is designated as that mineral material, and the Drucker-Prager intrinsic model with an isotropic damage model is chosen to study the damage pattern between the same materials, and the detailed calibration method can be found in a previous study (Liu *et al.* 2019). If the nodes of a grid cell are located in more than one mineral bin, respectively, the cell is considered as the boundary of different mineral grains (i.e., inter-grain bonds) and is used to model the state of inter-grain connections within the granite. To improve the computational speed, only the part of the cutter cutting is modeled as inhomogeneous, the size of this part is  $26 \times 25 \times 5.5$  mm, the mesh size is 0.2 mm, a total of 455000 cells, which can meet the requirements of single cutter cutting, and the rest of the rock sample is given the "Quartz" property. The generated non-homogeneous granite model is displayed in Fig. 3.

The composition, mass fraction, mineral grains and bonded material properties of each mineral in the granite model are shown in Table 1 below.

### 3.2 Rock cutting model of worn SSC

Wear failure is the most common failure form of PDC bit in rock cutting. Fig. 4(a) depicts a schematic diagram of the Wear failure of PDC bit, from which the wear section of PDC cutter is approximately a flat surface, while the edge line of cutter is approximately a chord truncated circle. This

Table 1 Mineral composition and material properties of granite

Mineral	Mass fraction (%)	Young's modulus (GPa)	Poisson's ratio	Compressive strength (MPa)	Grain size (mm)
Muscovite	7.8	32	0.16	167	1~1.8
Quartz	12.2	75	0.08	187	2~3
Albite	34.5	55	0.12	137	3~4
Microcline	41.1	53	0.13	147	1.2~2
Chlorite	4.4	48	0.14	137	1~2
Boundary		22.2	0.168	67	

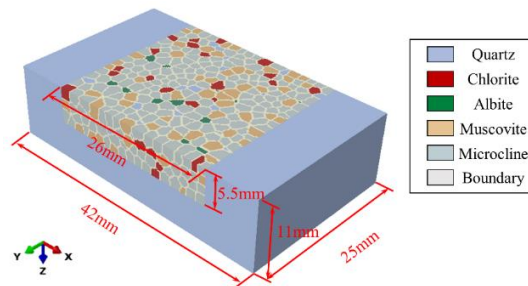


Fig. 3 Numerical simulation model of non-homogeneous granite

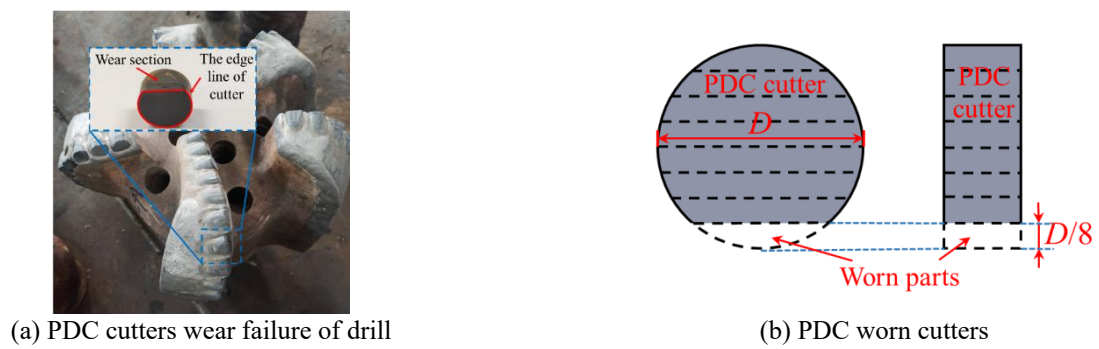


Fig. 4 Schematic diagram of PDC cutter wear

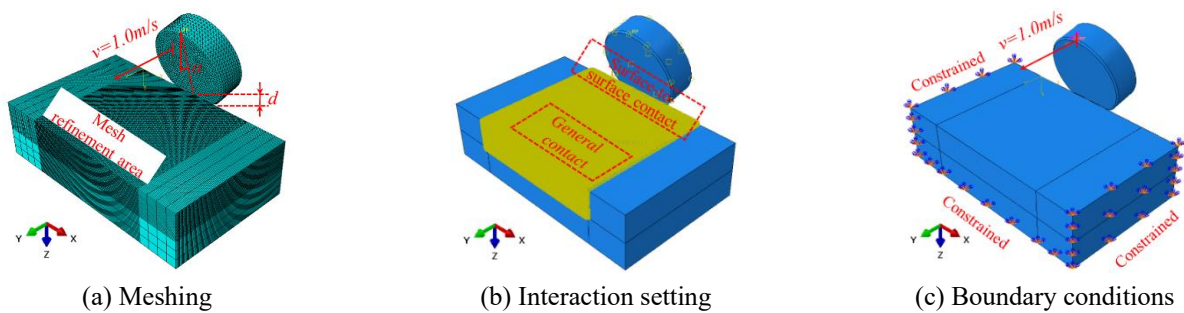


Fig. 5 Planar PDC worn cutter cutting broken granite model

paper defines the worn height of PDC cutter about 1/8 of the diameter of cutter referencing the PDC cutter regulations of the International Association of Drilling Contractors (IADC), the worn PDC cutter used in this study is shown in Fig. 4(b).

To facilitate the computational analysis, the following hypothesis are made, the strength and hardness of the cutter is much higher than the rock and the cutter is set as rigid body, ignoring the subsequent wear of cutter during the cutting process. When the rock unit fails, it is removed from

the intact rock and the effect of the failed unit on the subsequent cutting is ignored. The bottom surface and the both the left and right sides of the rock model are constrained. The contact properties between PDC cutter and granite model are selected the surface-to-surface contact, and the mesh in granite model are set as general contact, the friction coefficient between all contacts is 0.25; the cutting speed of PDC cutter is  $v=1.0$  m/s, and the cutting distance is 26 mm.

The rock cutting behavior of different SSC are studied

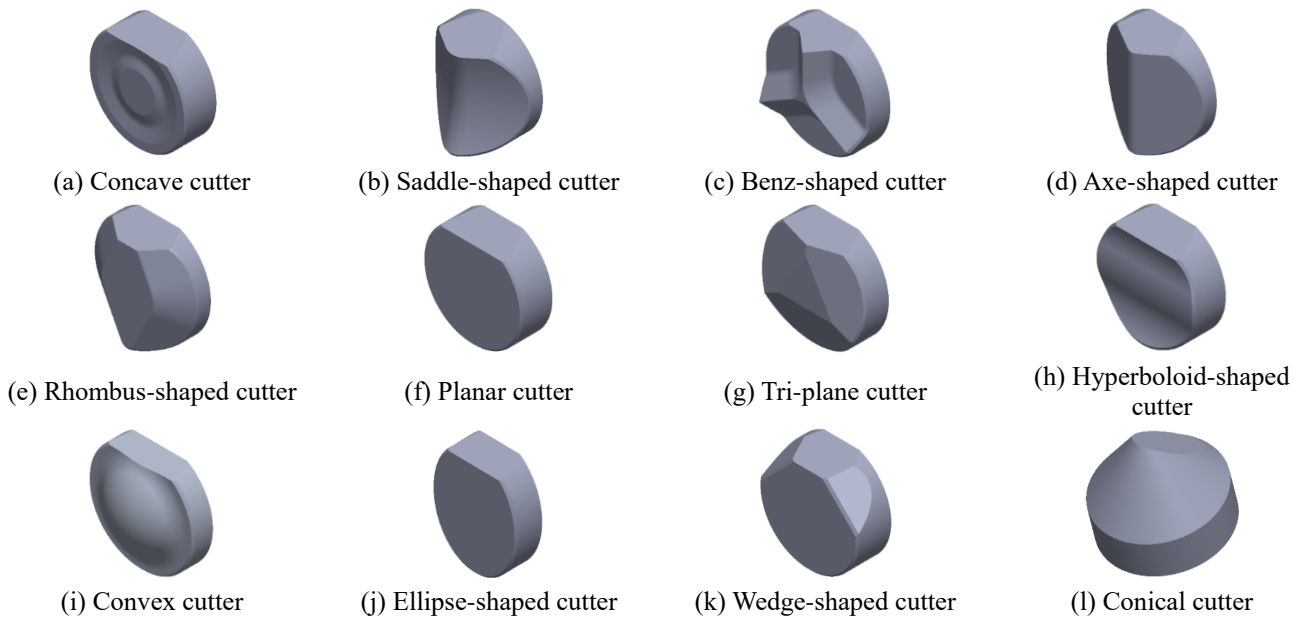


Fig. 6 Specially-shaped PDC worn cutters for simulation

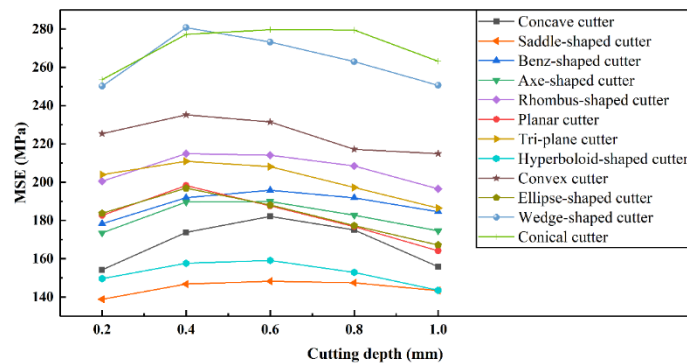


Fig. 7 Variation law of MSE with cutting depth for specially-shaped PDC worn cutters

under different cutting depths and back rake angles. The cutting depth ranges from 0.2 to 1.0 mm with 0.2 mm increments, and the back rake angle ranges from 0 to 20° with 5° increments. The rock cutting simulation model of worn PDC cutter is shown in Fig. 5.

The shapes of PDC cutter include Concave cutter, Saddle-shaped cutter, Benz-shaped cutter, Axe-shaped cutter, Rhombus-shaped cutter, Planar cutter (conventional cutter), Tri-plane cutter, Hyperboloid-shaped cutter, Convex cutter, Ellipse-shaped cutter, Wedge-shaped cutter and Conical cutter, and the geometry of each worn SSC is shown in Fig. 6.

#### 4. The rock cutting performance of SSC

##### 4.1 Effect of cutting depth and back rake angle on rock cutting efficiency

From the previous analysis, it is known that the rock-breaking efficiency of worn SSC is evaluated using the MSE, the smaller the MSE, the higher the rock-breaking efficiency SSC.

Fig. 7 displays the MSE with respect to the cutting depths of various worn SSC, the back rake angle is fixed at 15°. It can be seen that with the increase of cutting depth, the MSE of each worn SSC increases first and then decreases gradually, which indicates that different shape cutters have the corresponding optimal cutting depth. And from the results in Fig. 7, most of the SSC reach the maximum MSE when the depth of cut is 0.4 or 0.6 mm, so we can avoid these cutting depths when selecting cutting parameters. The MSE value of various worn SSC illustrate that Conical cutter and Wedge-shaped cutter have the largest MSE among all cutters, the MSE of Planar cutter and Ellipse-shaped cutter is basically the same in different depths. when the depth of cut is relatively small (0.2 mm or 0.4 mm), the MSE of Benz-shaped cutter and Axe-shaped cutter are lower than Planar cutter. The MSE of Concave cutter, Saddle-shaped cutter and Hyperboloid-shaped cutter is lower than Planar cutter at all cutting depths. Therefore, if the evaluation is made only in terms of the MSE, the rock-breaking efficiency of conical cutter and wedge-shaped cutter is the lowest, and the rock-breaking efficiency of concave cutter, saddle-shaped cutter and hyperboloid-shaped cutter is better than that of planar cutter.

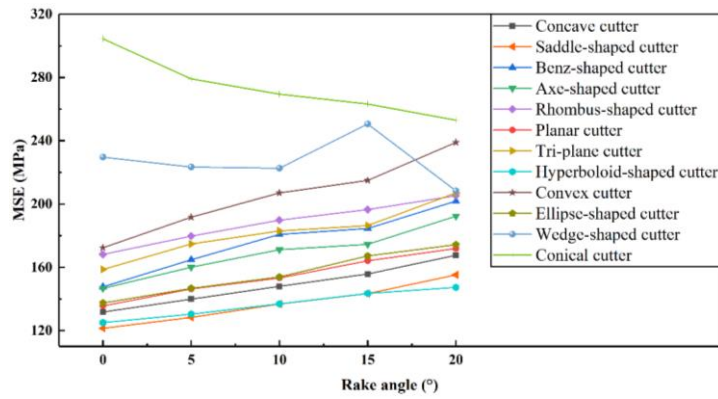


Fig. 8 Variation law of MSE with rake angle for specially-shaped PDC worn cutters

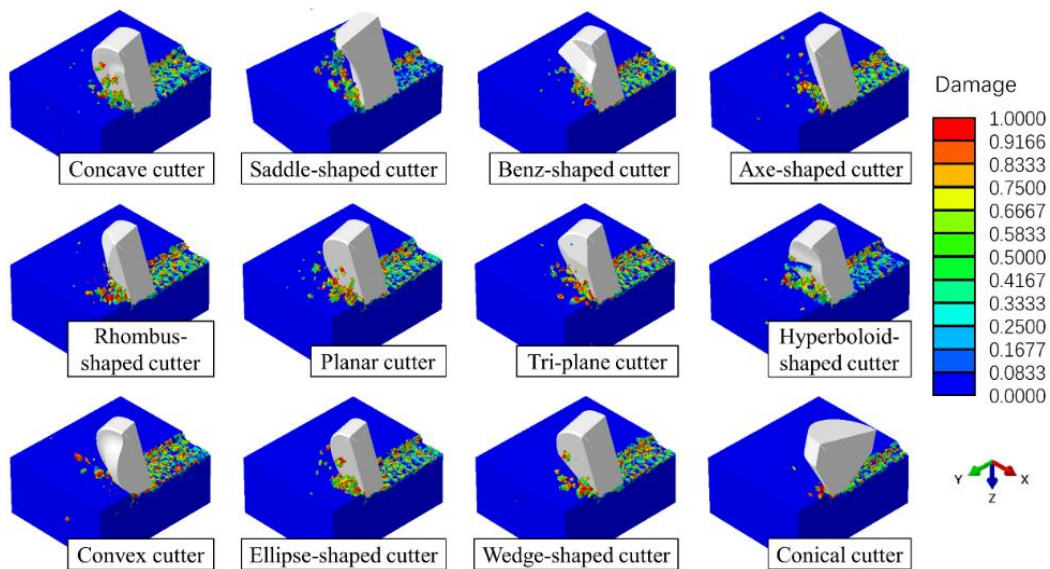


Fig. 9 Rock-breaking nephogram of specially-shaped PDC worn cutters

Fig. 8 presents the variation law of MSE with rake angle for various worn SSC. The MSE of conventional Planar cutter is about 140~160 MPa. The MSE of Conical cutter and Wedge-shaped cutter decreases with increasing the back rake angle. The MSE of other worn SSC increases roughly with the increase of the back rake angle. In the same cutting rake angle, the MSE of Concave cutter, Saddle-shaped cutter and Hyperboloid-shaped cutter is lower than that Planar cutter. Similarly, the MSE of Ellipse-shaped cutter is still the same with Planar cutter, the MSE of all other specially-shaped cutters is higher than Planar cutter. Among all specially-shaped cutters, the MSE of conical cutter is the largest and that of saddle-shaped cutter is the smallest. Therefore, higher rock cutting efficiency can be obtained by using Concave cutter, Saddle-shaped cutter and Hyperboloid-shaped cutter instead of conventional Planar cutter. The back rake angle is recommended as 20° for Conical cutter and Wedge-shaped cutter, and the rake angle is recommended 0° for all other specially-shaped cutters.

A nephogram of rock cutting by worn SSC is shown in Fig. 9. The depth of cut shown in Fig. 9 is 1.0 mm and the back rake angle is 15°.

#### 4.2 The effect of cutting depth on the rock cutting performance

From the previous analysis, it is known that the rock cutting performance of SSC should not be evaluated only at the perspective of rock cutting efficiency, but should take full account of its LP. Therefore, in order to investigate the rock cutting performance of each worn SSC and its variation with depth of cut and rake angle, the following analysis will be carried out in terms of the aggressiveness, stress concentration coefficient and loading performance coefficient of each cutter.

Fig. 10 depicts the aggressiveness of worn SSC vs the cutting depths. The aggressiveness of all cutters are decrease with increasing the cutting depth, especially, the Conical cutter, Concave cutter and Convex cutter. It can also be found that the aggressiveness of all specially-shaped cutters are greater than that of Planar cutter, except for the Convex cutter and Wedge-shaped cutter, so the corresponding specially-shaped cutters can penetrate into the rock more easily.

Fig. 11 plots the variation of stress concentration

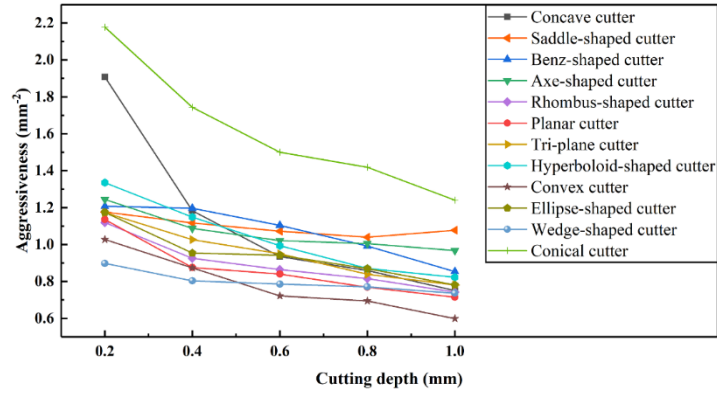


Fig. 10 Variation law of aggressiveness with cutting depth for specially-shaped PDC worn cutters

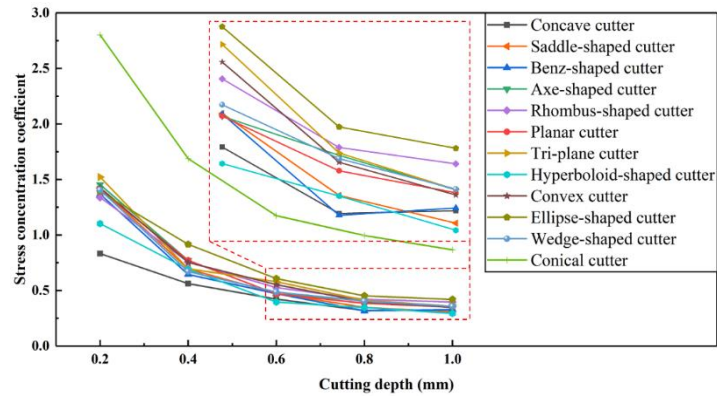


Fig. 11 Variation law of stress concentration coefficient with cutting depth for specially-shaped PDC worn cutters

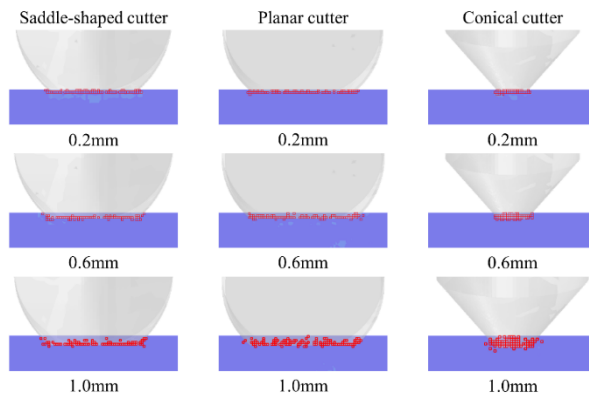


Fig. 12 Location distribution of maximum Mises stress on rock with depth of cut during cutting of specially-shaped PDC worn cutters

coefficient with depth of cut. From the analysis of stress concentration coefficient in section 1.2, it can be seen that the smaller the stress concentration coefficient value, the more concentrated the cutter stress distribution, and the easier the cutter damaged. The stress concentration coefficient of Conical cutter is larger than the other specially-shaped cutters obviously, which means that the stresses distribution on Conical cutter are more uniform. The stress concentration coefficient of Concave cutter, Saddle-shaped cutter and Hyperboloid-shaped cutter are smaller than Planar cutter, it infers that the stress distribution on these cutters are more concentrated than conventional Planar cutter. It is also found that the values of

the stress concentration coefficients of all cutters generally show a decreasing trend as the depth of cut increases, except for the Concave cutter and Benz-shaped cutter.

Fig. 12 reveals the location Mises stress distribution of rock with different cutting depths for the Saddle-shaped cutter, Planar cutter and Conical cutter (the other SSC have similar change rules, and the those three typical cutters are selected here for analysis). The maximum Mises stress on rock is mainly distributed at the cutter edge. when the depth of cut is small, the stress on cutter is more uniformly distributed; when the depth of cut is large, the contact area of cutter increases with the increase of cutting depth. The ratio of the projected area of the maximum stress location to

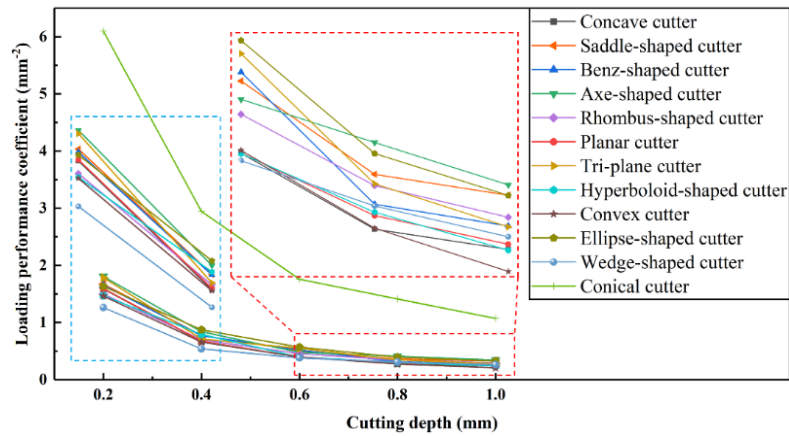


Fig. 13 Variation law of loading performance coefficient with cutting depth for specially-shaped PDC worn cutters

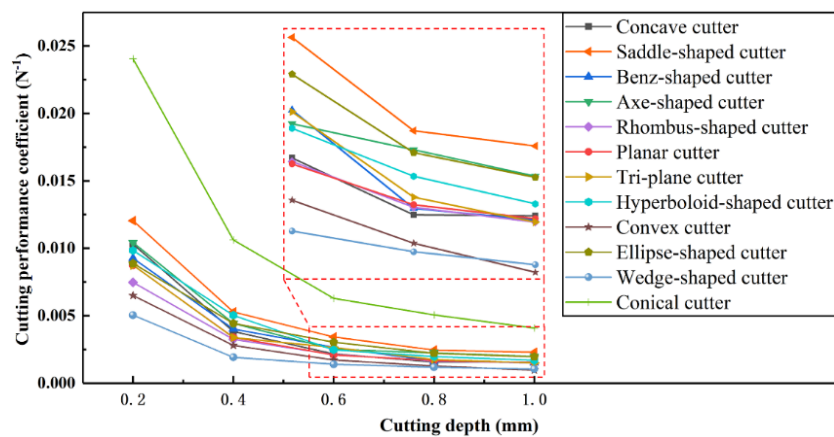


Fig. 14 Variation law of cutting performance coefficient with cutting depth for specially-shaped PDC worn cutters

the projected cutting area of the cutter (i.e., the stress concentration coefficient) decreases with the increase of the cutting depth, which is also consistent with the results in Fig. 11.

Fig. 13 plots the variation law of LP coefficient with cutting depths. The LP coefficient is a comprehensive reflection of the aggressiveness and stress concentration coefficient of SSC, which is an important index for comprehensive evaluation of cutter stress. The larger the LP coefficient, the more the aggressiveness of the cutter. As can be seen from Fig. 13, the LP coefficient of each cutter decreases with the increase of cutting depth, which means that the LP of SSC decreases with increasing the cutting depth. It is not difficult to find that this is also consistent with the previous results, when the depth of cut is small, the stress distribution of cutter is more uniform, and the aggressiveness is stronger, so the LP is better in combination. The LP coefficient of conical cutter is always greater than the other SSC, the Conical cutter is more excellent in the perspective of stress distribution. The LP coefficient of Wedge-shaped cutter and Convex cutter is the smallest, so the stress performance of Wedge-shaped cutter and Convex cutter is poorer. The LP coefficient of all specially-shaped cutters is greater than conventional Planar cutter except for Wedge-shaped cutter, Convex cutter, Hyperboloid-shaped cutter and Rhombus-shaped cutter,

which indicates that the stress performance of specially-shaped cutters is roughly better than Planar cutter, so in practical application, specially-shaped cutters can be considered to replace Planar cutter to extend the service life of PDC cutters.

Fig. 14 plots the CP coefficient with respective to the cutting depths. It can be seen that the CP coefficient of worn SSC decreases with the increase of cutting depth, and the decreasing trend tends to level off gradually. Therefore, it can be known that both conventional cutter and specially-shaped cutters are more suitable for smaller cutting depths after wear.

The CP coefficients of Saddle-shaped cutter, Axe-shaped cutter, Hyperboloid-shaped cutter, Ellipse-shaped cutter and Conical cutter are larger than conventional Planar cutter. The large value of CP means the better performance of SSC, which is opposite to the results of MSE in Fig. 7. It also shows that the performance of cutter cannot be evaluated simply by using the MSE. The CP coefficient of Rhombus-shaped cutter, Convex cutter and Wedge-shaped cutter is lower than conventional Planar cutter, which indicates these specially-shaped cutters should be avoided in practical use. The CP coefficient of Concave cutter, Benz-shaped cutter and Tri-plane cutter is not much different from Planar cutter, but it can be seen from Fig. 13 that the LP coefficient of Benz-shaped cutter and Tri-plane

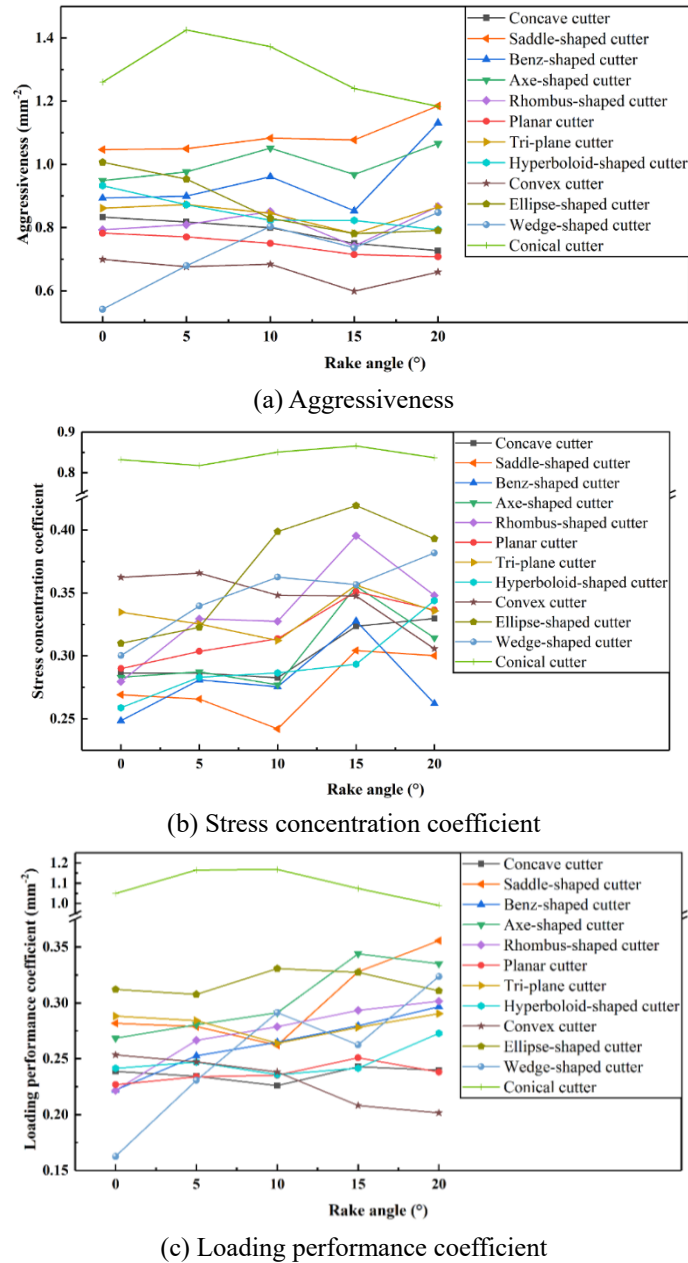


Fig. 15 The variation of aggressiveness, stress concentration coefficient, and loading performance coefficient of specially-shaped PDC worn cutters with rake angle

cutter is larger than Planar cutter, so these two specially-shaped cutters can still be used to replace planar cutter.

#### 4.3 The effect of back rake angle on rock cutting performance

The back rake angle of cutter is an important parameter in rock cutting, and it will directly affect the cutting efficiency. Therefore, the effect of back rake angle on LP and CP of worn SSC is conducted, the cutting depth is a constant of 1.0 mm.

Fig. 15 depicts the variations of aggressiveness, stress concentration coefficient and LP of worn SSC versus back rake angle respectively. As shown in Fig. 15(a), the aggressiveness of SSC is larger than Planar cutter except for

the Convex cutter, among them, the aggressiveness value of Conical cutter and Saddle-shaped cutter is significantly larger than other cutters at different back rake angles, the aggressiveness of Convex cutter is the smallest. The results show that specially-shaped cutters have stronger aggressiveness compared with conventional Planar cutter, and proper use of specially-shaped cutters can improve rock-breaking efficiency.

The aggressiveness of Convex cutter, Planar cutter, Concave cutter, Hyperboloid-shaped cutter and Ellipse-shaped cutter decreases with the increase of back rake angle. It can be seen from the Fig. 6 that the effect of the shaped structure of cutter on the projection area of  $S_p$  in Eq. (6), i.e., is almost negligible with the back rake angle increases, the projection area is similar to conventional

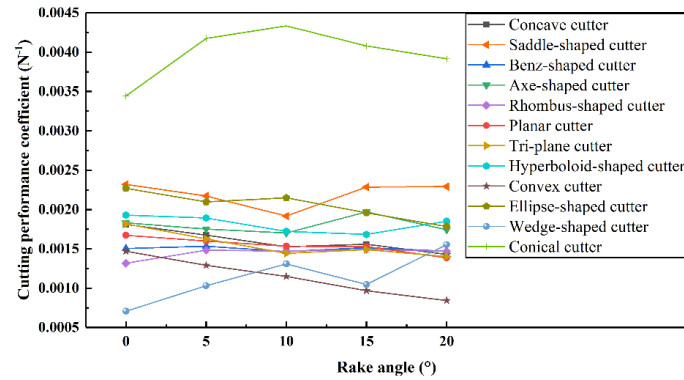


Fig. 16 Cutting performance coefficient of specially-shaped PDC worn cutters with the variation law of rake angle

Planar cutter. Therefore, the aggressiveness of these specially-shaped cutters has a similar variation law. To facilitate the subsequent analysis, these specially-shaped cutters are collectively referred to as "cylindrical class", and it can be seen from Fig. 15(a) that, large back rake angle should be avoided in using "cylindrical class" cutters from the perspective of aggressiveness. The Wedge-shaped cutter, Rhombus-shaped cutter, Tri-plane cutter, Benz-shaped cutter, Axe-shaped cutter and Saddle-shaped cutter are collectively called "ridge-shaped". In order to improve the aggressiveness of "ridge-shaped" cutters, the back rake angle is recommended 20° instead of 15°. The aggressiveness of Conical cutter first increases and then decreases, and reaches the maximum value at the back rake angle of 5°, the optimal back rake angle is recommended 5°.

Fig. 15(b) represents the variation of the stress concentration coefficient with back rake angle. The stress concentration coefficient of Conical cutter is significantly larger than the other specially-shaped cutters, it indicates the stress distribution on cutter is more uniform. The stress concentration coefficients of Ellipse-shaped cutter and Wedge-shaped cutter are larger than conventional Planar cutter, the stress concentration coefficients of Rhombus-shaped cutter are larger than Planar cutter except the back rake angle of 0°. The stress concentration coefficients of Saddle-shaped cutter, Benz-shaped cutter, Concave cutter and Hyperboloid-shaped cutter (except for back rake angle of 20°) are smaller than Planar cutter. The stress concentration coefficients of Convex cutter and Tri-plane cutter are smaller than Planar cutter.

Fig. 15(c) shows the variation of the LP coefficient of worn SSC with back rake angle. The LP coefficient of Conical cutter is the largest among the specially-shaped cutters. The LP coefficient of conventional Planar cutter is about 0.225–0.25 mm<sup>-2</sup>, which is at a lower level among all the specially-shaped cutters. Only individual specially-shaped cutters have a lower LP coefficient than Planar cutter at certain rake angles. It means that the SSC can improve the stress condition of cutters under most of the rake angles.

Fig. 16 illustrates the variation of CP coefficient of worn SSC in regard to back rake angle. The CP coefficient of Conical cutter is still much larger than other shaped cutters, and the CP coefficient of Conical cutter is the smallest at 0° and the largest at 10°, so the recommended back rake angle

are 5° and 10°. The CP coefficient of Saddle-shaped cutter, Ellipse-shaped cutter, Hyperboloid-shaped cutter and Axe-shaped cutter is greater than Planar cutter, and the CP coefficient of these specially-shaped cutters decreases with the increase of back rake angle, so they are recommended with a small rake angle. The CP coefficient of Convex cutter and wedge-shaped cutter are smaller than Planar cutter, and the back rake angle are recommended 0°, the back rake angle of Wedge-shaped cutter is recommended 20°. In the process of increasing the rake angle from 0° to 20°, the CP is affected by the rake angle of several specially-shaped cutters are Conical cutter, Ellipse-shaped cutter, Convex cutter and Wedge-shaped cutter, and the CP coefficient of most of the remaining shaped cutters does not fluctuate much with the change of the rake angle, and is more gentle compared with the different depth of cut, which means that the CP of worn SSC is less sensitive to the change of the rake angle than the change of the depth of cut. When the depth of cut is 1.0mm, the Conical cutter, Ellipse-shaped cutter, Saddle-shaped cutter, Benz-shaped cutter and Hyperboloid-shaped cutter can be considered to replace the conventional Planar cutter when balancing the rock-breaking efficiency and working life of cutters.

#### 4.4 Parameter optimization and performance evaluation of worn SSC

To visualize the recommended depth of cut and back rake angle of each worn SSC, the CP coefficient of each worn SSC with fixed cutting depth and back rake angle is arranged in a descending order, and the cutter selection efficiency of worn SSC and selection priority are list in Fig. 17. The SSC with larger CP coefficient than conventional Planar cutter is called recommended cutters, and the corresponding cutter selection efficiency is greater. In contrast, the specially-shaped cutters with the CP coefficient is less than Planar cutter is called non-recommended cutters. The conventional Planar cutter is marked in red, the recommended SSC are marked in green, and the non-recommended cutters are marked in orange. It is also known from Fig. 17 that the benefits and priorities of cutter selection for Conical cutter, Saddle-shaped cutter, Ellipse-shaped cutter, Axe-shaped cutter and Hyperboloid-shaped cutter are higher than those of conventional Planar cutter, while

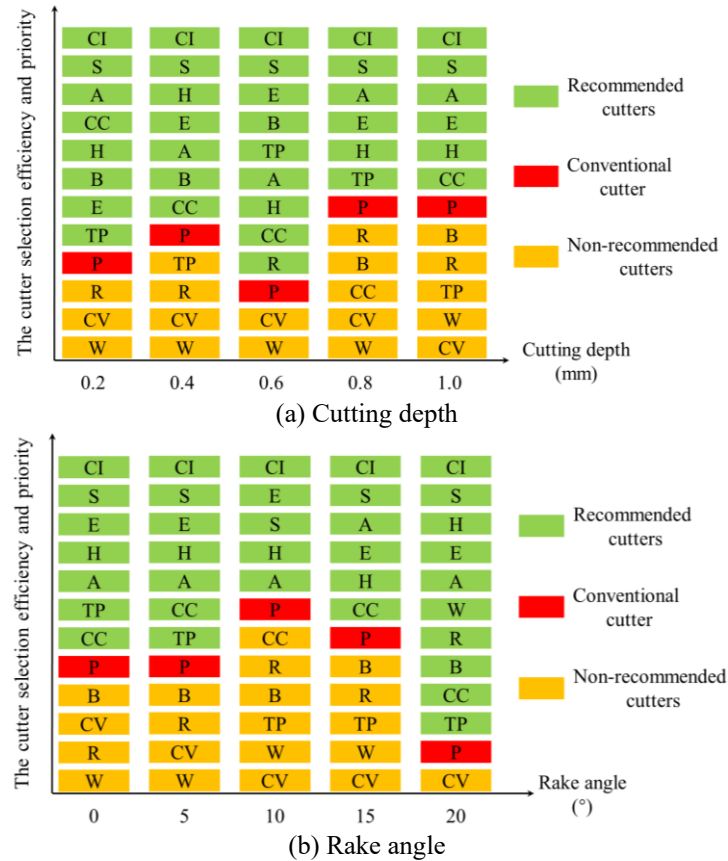


Fig. 17 The cutter selection efficiency and priority of specially-shaped PDC worn cutters (CC: Concave cutter; S: Saddle-shaped cutter; B: Benz-shaped cutter; A: Axe-shaped cutter; R: Rhombus-shaped cutter; P: Planar cutter; TP: Tri-plane cutter; H: Hyperboloid-shaped cutter; CV: Convex cutter; E: Ellipse-shaped cutter; W: Wedge-shaped cutter; CI: Conical cutter)

Table 2 The recommended cutting rake angles of specially-shaped PDC worn cutters

Cutter profile	Recommended rake angles(°)	Cutter profile	Recommended rake angles(°)
Concave cutter	0	Tri-plane cutter	0
Saddle-shaped cutter	0, 15~20	Hyperboloid-shaped cutter	0~5
Benz-shaped cutter	0~5, 15	Convex cutter	0
Axe-shaped cutter	15	Ellipse-shaped cutter	0
Rhombus-shaped cutter	5, 15	Wedge-shaped cutter	20
Planar cutter	0	Conical cutter	5~10

Convex cutter are not recommended. Conical cutter and Saddle-shaped cutter have the highest recommended priority, while Rhombus-shaped cutter and Wedge-shaped cutter have the narrowest recommended range for application. Rhombus-shaped cutter is only recommended when the depth of cut is 0.6 mm and the back rake angle is 15° or when the depth of cut is 1.0 mm and the rake angle is 20°, and Wedge-shaped cutter is only recommended when the depth of cut is 1.0 mm and the rake angle is 20°.

By comparing the relationship of CP of each worn SSC with the back rake angle (as shown in Fig. 16), the back rake angle of each worn SSC can be preferred, and the recommended back rake angles of each worn cutter is list in Table 2.

In addition, the performance of each worn SSC can be evaluated by using the indexes in the theoretical analysis section, including the aggression performance, the stress distribution, the force effectiveness, the rock cutting efficiency and the cutter selection efficiency. The cutter selection efficiency is determined by the LP and CP, the cutter selection efficiency is determined by the CP coefficient  $\lambda$ . The larger the CP coefficient  $\lambda$ , the higher the corresponding cutter selection benefit priority. the rock cutting efficiency is determined by the MSE, the lower the value of MSE, the higher the rock cutting efficiency. The LP is determined by the aggression performance and stress distribution, the LP is determined by the LP coefficient  $\eta$ , and the larger the LP coefficient  $\eta$ , the better the LP of cutter. The aggression performance is measured by the aggressiveness  $\phi$ , the larger the aggressiveness  $\phi$ , the stronger the aggression performance; the measure of the stress distribution is the stress concentration coefficient  $\xi$ , the larger the stress concentration coefficient  $\xi$ , the more uniform the stress distribution of cutter.

Table 3 Performance evaluation table of specially-shaped PDC worn cutters

Evaluation Indicators Cutter profile	Aggression performance	Force distribution	Loading performance	Cutting performance	Cutter selection benefit
Concave cutter	Medium	Medium	Poor	Excellent	Good
Saddle-shaped cutter	Excellent	Poor	Good	Excellent	Excellent
Benz-shaped cutter	Good	Poor	Medium	Medium	Medium
Axe-shaped cutter	Excellent	Medium	Excellent	Good	Good
Rhombus-shaped cutter	Medium	Good	Good	Medium	Poor
Planar cutter	Poor	Medium	Good	Good	Medium
Tri-plane cutter	Medium	Good	Poor	Medium	Medium
Hyperboloid-shaped cutter	Good	Poor	Medium	Excellent	Good
Convex cutter	Poor	Good	Poor	Poor	Poor
Ellipse-shaped cutter	Good	Excellent	Excellent	Good	Excellent
Wedge-shaped cutter	Poor	Excellent	Medium	Poor	Poor
Conical cutter	Excellent	Excellent	Excellent	Poor	Excellent

To comprehensively measure the advantages and disadvantages of each performance index of worn SSC, the performance indexes of the 12 worn specially-shaped PDC cutters in this study are classified into four evaluation levels from high to low, excellent, good, medium and poor. The performance indexes are the average values under different back rake angles of the worn specially-shaped PDC cutters at the depth of cut of 1.0 mm, namely

$$I_a = \frac{1}{n} \sum_{i=1}^n I_i \quad (9)$$

where the  $I_a$  is a measure of performance, specifically one of the mean value of aggressiveness  $\varphi_a$ , the mean value of stress concentration coefficient  $\xi_a$ , the mean value of stress benefit coefficient  $\eta_a$ , the mean value of mechanical specific energy  $MSE_a$  and the mean value of CP coefficient  $\lambda_a$ ;  $n$  is the number of performance measures, here  $n=5$  (5 kinds of rake angle);  $I_i$  is the  $i$ th value of a performance measure.

By comparing the relative magnitudes of each performance measure, the performance advantages and disadvantages of a certain worn SSC can be derived. The ranking of each performance measure from high to low (mean value of aggressiveness  $\varphi_a$ , mean value of stress concentration coefficient  $\xi_a$ , mean value of LP coefficient  $\eta_a$  and mean value of CP coefficient  $\lambda_a$ ) or from low to high (mean value of mechanical specific energy  $MSE_a$ ) can be obtained from excellent to poor performance, as shown in Table 3.

As can be seen from Table 3, Conical cutter, Ellipse-shaped cutter and Saddle-shaped cutter have the best cutter selection benefits. although the Conical cutter has low rock cutting efficiency, but it make up for the lack of rock cutting efficiency by virtue of the highest aggression performance, stress distribution and LP. Ellipse-shaped cutter, on the other hand, have the combined advantages of excellent stress distribution and LP as well as good aggression performance and rock-breaking efficiency, making their cutter selection benefits better than most of the specially-

shaped cutters. Although the stress distribution of the Saddle-shaped cutter is poor, it achieves excellent cutter selection benefit by virtue of its better LP and excellent aggression performance and rock cutting efficiency. Although the stress distribution of axe-shaped cutter is average, its high cutting efficiency combined with excellent LP and aggressiveness makes its cutter selection benefit also reach good. The LP or stress distribution of Concave cutter and Hyperboloid cutter is poor, but their rock cutting efficiency is high, so the comprehensive cutter selection benefit is also good. Benz-shaped cutter, Planar cutter and Tri-plane cutter have average cutter selection benefits. Benz-shaped cutter have poor stress distribution, good aggression performance, average LP and rock cutting efficiency, and average cutter selection benefits. Conventional Planar cutter have good LP and rock cutting efficiency, but their stress distribution is average, aggression performance is poor, and overall cutter selection benefits are average. Tri-plane cutter have poor LP, but the comprehensive cutter selection efficiency is still at an average level because of its good stress distribution and general aggression performance and rock cutting efficiency. The Rhombus-shaped cutter have good stress distribution and LP, average aggression performance and rock cutting efficiency, and poor overall cutter selection benefit. The Convex cutter and Wedge-shaped cutter have low rock cutting efficiency, poor aggression performance, and average or poor LP, so the overall cutter selection benefit is the lowest.

## 5. Conclusions

In this paper, the theoretical models of LP and CP are derived for evaluating the cutting process of worn specially-shaped cutter, the theoretical models consider the factors, such as cutter geometry, aggressiveness, stress state, working life, and rock cutting efficiency. Besides, the numerical model of heterogeneous granite is developed

using finite element method combined with Voronoi tessellation, the LP and CP of 12 kinds of worn specially-shaped PDC cutters are analyzed. The following conclusions can be drawn,

- The MSE of worn specially-shaped PDC cutters first increases and then decreases with increasing the cutting depth; the Saddle-shaped cutter and Hyperboloid-shaped cutter have the lowest MSE, and the Wedge-shaped cutter and conical cutter have the largest MSE value. The MSE of Conical cutter and Wedge-shaped cutter are decreasing with the increase of back rake angle, the MSE of other SSC are increasing with the back rake angle.
- The aggressiveness, stress distribution, LP and CP of worn specially-shaped PDC cutters decrease with the increase of cutting depth. The smaller the cutting depth, the stronger the aggressiveness of worn cutter, the more uniform the stress distribution on cutter surface, the better the LP and CP. Therefore, the worn PDC cutter is more suitable for using with small cutting depth.
- Conical cutter, Saddle-shaped cutter and Ellipse-shaped cutter have the best cutter selection benefits, conventional Planar cutter have average cutter selection benefits, and Rhombus-shaped cutter, Convex cutter and Wedge-shaped cutter have the worst cutter selection benefits. Although the MSE of Conical cutter is the lowest, its aggression performance, stress distribution and LP are the best, which makes up for its disadvantage of low rock-breaking efficiency, thus the comprehensive CP is the best. Although the stress distribution of Wedge-shaped cutter is good, but its aggression performance and rock-breaking efficiency are very poor, which makes its comprehensive CP the worst.

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