Numerical investigation on rock-breaking mechanism and cutting temperature of compound percussive drilling with a single PDC cutter

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Abstract
Compound percussive drilling technology is a new method to improve the rock-breaking efficiency in deep hard formation. In order to study the rock-breaking mechanism of compound impact drilling, the thermal-structure coupling simulation of the dynamic rock-breaking process with a single PDC cutter was investigated by using ABAQUS software. The influence of impact parameters on the rock-breaking performance and cutting temperature was analyzed. The results proved that the compound impact load changes the rock failure mode and improves the rock-breaking efficiency. Compared with steady load cutting, the rock broken volume under compound impact increased by 7.5%, and the mechanical specific energy (MSE) decreased by 12.3%. As the axial impact load amplitude increases, the MSE increases gradually. With an increase in torsional impact load amplitude and impact frequency, the MSE decreases first and then increases, and the optimal torsional static load ratio is 0.3, and the optimal impact frequency is 30 Hz. In addition, the cutting temperature of the compound percussive drilling is higher than that of the steady load cutting, and it increases with the impact load amplitude and decreases with the frequency. For the three impact load waveforms—sine, triangle, and square in this paper, the rock-breaking efficiency under the condition of sine waveform is the largest when the dynamic amplitude of the pulse force is fixed, and the cutting temperature under the condition of square waveform is the highest. Finally, based on the analysis of the rock-breaking mechanism, a novel compound percussive drilling tool was designed and tested in the field.

KEYWORDS
compound percussive drilling, cutting temperature, MSE, PDC cutter, rock-breaking efficiency
1 | INTRODUCTION

In drilling engineering, the PDC bit is suitable for homogeneous formation from soft to medium-hard due to its good wear resistance and self-sharpening. The footage drilling in oil and gas wells of PDC bits has increased from 2% in 1982 to 90% in 2019.\(^1\)\(^-\)\(^4\) With the focus of oil and gas exploration shifting from shallow to deep, the rock becomes high strength, strong abrasiveness, and poor drillability.\(^5\) Simultaneously, with the increase of drilling depth, it becomes more challenging to apply weight on bit (WOB) and torque on bit (TOB). These reasons lead to low rock-breaking efficiency of PDC bit and high drilling cost. It is necessary to strengthen the current drilling technology to achieve high quality and fast drilling. Thus, different types of percussive drilling technology have been proposed to improve the rock-breaking efficiency of PDC bit.\(^6\)\(^-\)\(^8\) The principle of percussive drilling technology is to use percussive drilling tools to convert drilling fluid energy into periodic impact energy to act on the bit, which can adapt to the high-speed rotation of the PDC bit, improve rate of penetration (ROP), and prevent premature failure of the PDC bit.

At present, rotary percussive drilling and torsional impact drilling technology are the most widely studied and applied percussive drilling technologies, which can be seen from previous studies.\(^8\)\(^-\)\(^12\) Compound impact drilling technology combined the advantages of rotary and torsional percussion drilling technology, which can provide additional instantaneous WOB and TOB for bit simultaneously.\(^13\),\(^14\) The rock below and in front of the cutter could be destroyed under the compound impact, forming a three-dimensional rock-breaking effect.\(^5\)\(^,\)\(^15\) In recent years, the rock-breaking mechanism of compound impact drilling has been studied and analyzed, and various types of the tool have been designed. Zha et al\(^16\) designed a novel combined percussion jet tool and analyzed its rock-breaking process, and the results show that the percussive tool can produce higher shear stress in rock formations. Mu et al\(^17\) developed an axial-torsional coupled percussive drilling tool and analyzed the tool performance through theoretical calculations, indoor tests, and field tests, and the study results showed that the ROP of the test well could be increased by 1.6-3.3 times after using axial-torsional coupled percussive drilling. Li et al\(^18\) built a numerical method for modeling PDC single cutter-rock impact system and studied the effects on the dynamic rock-breaking mode and rock-breaking performance under the combined action of rotating speed, drilling pressure, alternating impact torque, and alternating impact force. Song et al\(^5\) established a 3D percussive system model by using finite element method to study the energy transfer efficiency in the rock-breaking process of axial-torsional coupled percussive drilling. Liu et al\(^19\) proposed a finite element analysis model considering the strain rate effect. Based on the above model, the influence of vertical and horizontal impact load on cutting mode was studied. Liu et al\(^20\) studied the formation of cuttings and specific energy of rock breaking during compound impact drilling through a pseudo-three-dimensional numerical simulation model.

Moreover, apparent friction between the PDC cutter and the rock occurs during the cutting process. This friction is responsible for elevating the temperature of the PDC cutter and causing thermal damage, reducing cutter life. Previous studies have shown that more than half of the energy supplied to the bit is converted into friction heat.\(^21\) Detournay found that higher temperature would lead to the decline of bit performance during rock breaking.\(^22\) Glowka developed a numerical-analytical method to predict temperatures in PDC cutters under downhole conditions and demonstrated the relationship between cutter temperature and wear rates.\(^23\) Loui proposed a two-dimensional transient heat transfer model. Based on this model, the temperature change of the cutter-rock interface was predicted.\(^24\) Zhang et al\(^1\) used the finite element method to simulate the thermal-structural coupling of rock-breaking process of the full-size PDC bit, obtained the high-temperature distribution area of the cutter, and analyzed the failure reason of the PDC cutter. Yang et al\(^25\) built a set of differential equations to describe the temperature change of the bit and studied the effects of geometric conditions, thermophysical properties, and drilling parameters on the bit temperature. Gao et al\(^26\) established a thermal elastoplastic damage model by using a finite element analysis system and the analyzed changes of stress state, strain accumulation, and heat transfer on the cutter during high-speed cutting. Zhou et al\(^27\) discussed the influence of rock properties on cutting temperature and analyzed the mechanism through laboratory tests. The results showed that rock strength is an essential factor affecting the temperature rise rate.

Although the compound impact drilling technology has demonstrated a certain ability to break hard rock formations, the mechanism of rock breaking and the change of cutting temperature have not been thoroughly studied. Therefore, it is necessary to conduct related research, so as to optimize the parameters of the tool and improve the compatibility between the tool and the hard rock formation, achieving the purpose of improving the rate of penetration. In this study, a 3D thermal-structural coupled numerical model composed of a single PDC cutter and hard rock was established, using the Drucker-Prager criterion as the rock yield criterion. Static and dynamic loads were applied to the cutter, and the rock-breaking mechanisms of steady load and compound impact drilling were analyzed and compared.
Then, the sensitivity analysis of impact parameters was carried out, and the effects of dynamic load amplitude, impact frequency, and waveform on the rock-breaking performance and cutting temperature were analyzed. Finally, the parameters of the compound impact drilling tool were optimized, and the structure diagram of the impact drilling tool was designed.

2 | ANALYTIC MODEL

2.1 | Model assumption

The working process of the PDC bit is essentially a process of cutting the rock from the bottom hole by the cutters, and the rock-breaking analysis of a single cutter is the basis of PDC bit performance research. A single cutter-rock interaction analysis model was established according to the working process of the PDC bit under compound impact load. In order to reduce the calculation complexity, the following assumptions are conducted: (a) The materials of cutter and rock are homogeneous, and the wear and passivation of the cutter are ignored; (b) ignore the heat transfer between drilling fluid and PDC cutter; (c) the thermal and mechanical properties of the PDC bit and rock materials do not change with temperature.

2.2 | Mechanical model

During the compound percussive drilling process, the percussive tool is directly installed above the PDC bit, as shown in Figure 1. The percussive hammer moves back and forth under the action of the high-pressure drilling mud, impacts the anvil, and exerts periodic compound percussive load on the bit. The PDC bit is subjected to continuous WOB, TOB, and periodic axial-torsional coupled impact loads, breaking the bottom hole rock.5

As shown in Figures 1C and 2, the cutter suffers the axial force $F_a$, exerted by WOB, the horizontal force $F_x$ exerted by TOB, and the periodic axial impact force $F_a$, the torsional impact force $F_t$ exerted by the compound percussive drilling tool. In addition, the cutter also suffers rock reaction force $N_p$, $N_b$, and friction force $S_f$, $S_b$ in the front and bottom surface, respectively, and $\theta$ is rake angle.

As shown in Figure 2, the force balance equation of a single cutter during the rock-breaking process of compound percussive drilling can be expressed as follows:

$$F_A + F_a = N_b + N_f \sin \alpha + S_f \cos \alpha$$
$$F_T + F_t = S_b + N_f \cos \alpha - S_f \sin \alpha$$

If $\mu$ is the friction coefficient between the cutter-rock interface,

$$\mu = \frac{S_f}{N_f} = \frac{S_b}{N_b}$$

Solving for $N_f$ and $S_f$, we get,

$$N_f = \frac{(F_A + F_a) - \mu (F_A + F_a)}{(1 - \mu^2) \cos \alpha - 2\mu \sin \alpha}$$
$$S_f = \frac{\mu (F_T + F_t) - \mu^2 (F_A + F_a)}{(1 - \mu^2) \cos \alpha - 2\mu \sin \alpha}$$
It can be known from formula (3) that the normal force exerted on the rock in front of the cutter increases with the growth of the horizontal load and decreases with the axial load.

2.3 Thermomechanical model

The thermomechanical model of a single cutter in the rock-breaking process is shown in Figure 3. The heat distribution is determined by the structure of the single cutter and rock-breaking mode. The generated heat area includes (a) the deformation heat generated by plastic deformation of rock in area I; (b) the friction heat generated by the friction between the cutter surface and rock, distributed in area II in front of the cutter and area III below the cutter. In the steady load cutting process, the heat is mainly distributed in area I and area II while the heat in area III is limited, which is similar to the heat distribution in the working process of milling tool. However, during the rock-breaking process under compound impact, the cutter intrudes into the rock under the dynamic impact load, resulting in a large amount of friction heat generated in area III.

According to the Fourier's law, the partial differential governing equation of heat conduction between rock and cutter is as follows:

$$
\lambda \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) - \rho c \left( u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} + w \frac{\partial T}{\partial z} \right) + Q = 0
$$

(4)

where \( \rho \) is density of rock, \( c \) is specific heat of rock, \( \lambda \) is heat conductivity of rock, \( T \) is temperature. \( Q \) is the generation rate at which mechanical energy is converted to heat. \( x, y, \) and \( z \) are spatial coordinates. \( u, v, \) and \( w \) are the velocity components of the heat source in the \( x, y, \) and \( z \) directions, respectively.

In the cutting process, the cutter slides across the rock surface at a certain speed. The heat in zone II is mainly generated from the friction between the rock and the front face of the cutter. Assuming that the cutter is subjected to uniform and stable friction heat flow, and all mechanical friction is converted into heat on the cutting surface. The heat generated can be expressed as,

$$
Q_f = \frac{\mu N_f v_f}{l_f w}
$$

(5)

Ignored the heat conduction to the surrounding medium, the part of the friction heat entering to the rock and the PDC cutter can be described as follows:

$$
Q_r = \xi Q_f
$$
$$
Q_c = (1 - \xi) Q_f
$$

(6)

where \( \xi \) is the distribution coefficient of heat.

The thermal response function of the cutter can be expressed as,

$$
f = \frac{T_c - T_0}{Q_c}
$$

(7)

Combining Equations (4)-(7), the average temperature of single cutter is as follows:

$$
T_c = T_0 + \frac{(1 - \xi) \mu N_f v_f}{l_f w} \frac{f}{l_f w}
$$

(8)

where \( T_0 \) is the initial temperature. \( \xi \) is the distribution coefficient between cutter and rock. \( v_f \) is the relative sliding speed of cutter and the cuttings. \( v_c \) is the horizontal cutting speed. \( l_f \) is the length of the friction contact surface in front of cutter. \( l_w \) is the length of the friction contact surface at bottom of cutter. \( w \) is the width of the cutter.
Formula (8) shows that the temperature of the cutter increases with the growth of the normal force $N_f$ and the relative sliding speed $v_f$. Moreover, the distribution coefficient of the heat $\alpha$, the thermal response function $f$, and the friction coefficient $\mu$ between cutter and rock will also affect the cutter temperature.

3 | NUMERICAL MODEL

3.1 | Establishing of cutter-rock interaction model

According to the hypothesis of the model, the single cutter-rock interaction model is shown in Figure 4. The cutter was consisting of a polycrystalline diamond (PCD) layer on a cemented carbide (WC-Co) substrate. The diameter of the cutter was 10 mm, the width of the PCD layer was set to 1 mm, the width of cemented carbide was set to 4 mm, and the rake angle was 15°. The geometric dimensioning of the rock model was 200 mm $\times$ 20 mm, as shown in Figure 4A. To minimize the amount of calculation, the thickness of the model was set to 0.1 mm. Both the rock and the cutter were meshed by the 8-node hexahedral linear reduced integral element (C3D8RT). To better simulate the dynamic rock-breaking process, the element size should be designed to approximate the actual particle size of the rock. Considering the accuracy and complexity of the calculation, the mesh on the top of the rock model was refined to ensure better simulation results, and the encrypted mesh size was set to 0.2 mm, as shown in Figure 4B.

3.2 | Boundary and load

During the simulation, the nodes on the bottom and side surfaces of the rock model were fully constrained in the X, Y, and Z directions. The cutter was set as a rigid body due to the hardness of the PDC cutter is much higher than the rock. A reference point with two translational degrees of freedom was defined, and then, a kinematic coupling constraint was defined with the reference point, and the controlled surface was the side surface of the cutter, as shown in Figure 4B. The Y direction load was applied on the reference point to simulate the WOB and axial impact load. Similarly, the cutting speed was set in the X direction to simulate the torque and torsional impact load on the bit. A surface-to-surface contact was adopted between the cutter and rock surface, and the friction coefficient was set to 0.5. Besides, the initial ambient temperature of the model was set to 25°C.

In the steady load cutting simulation, the axial static load exerts on the cutter is 100 N, and the horizontal cutting speed is fixed at 800 mm/s. In the simulation of percussive rock breaking, the additional axial dynamic load is set as periodic impact force, and the extratorsional dynamic load is set as periodic impact velocity. We define $k_a$ as the ratio of axial impact load amplitude to axial static load and $k_t$ as the horizontal impact speed amplitude to horizontal cutting speed.

3.3 | Constitutive model and failure criterion

In the simulation, the correctness of rock constitutive model will directly affect the accuracy of the results. Several material models, which could be used to represent the damage evolution of rock under impact load, were contained in the widely used commercial software ABAQUS. A large number of previous studies have shown that the plastic damage constitutive model based on Drucker-Prager criterion was suitable for describe the constitutive relationship of rock elements and simulate the dynamic rock-breaking process.
The Drucker-Prager model considers the effect of intermediate principal stress on rock failure and reflects the expansion caused by shear. The yield surfaces of the Drucker-Prager model on the meridional and π planes are shown in Figure 5. The yield surface function of Drucker-Prager yield criterion on the meridian plane is expressed as,

\[
F = t - ptan\beta - d = 0 \tag{9}
\]

In the above formula, \(t = \frac{q}{3} \left[ 1 + \frac{1}{k} - \left( 1 - \frac{1}{k} \right) \left( \frac{t}{q} \right)^3 \right] \) is the deviatoric stress parameter, and \(k\) is the specific value between triaxial compressive strength and triaxial tensile strength, \(p\) represents the equivalent compressive stress, \(d\) is the cohesion of material, and \(\beta\) is the slope of the linear yield surface projected on the \(p - t\) stress plane.

For the rock failure criterion, the PDC cutter mainly crushed rock by shearing, and the shear failure criterion was selected as the basis for judging rock failure in the simulation. When the equivalent plastic strain value of the rock elemental node reaches that of the material, the material begins to damage. After the failure of the rock element, it is removed from the rock body, ignoring the effect of its failure on subsequent rock fragmentation. The judge criterion of the plastic strain of rock breaking can be described as follows:

\[
\varepsilon^p = \leq \varepsilon_f^p \tag{10}
\]

3.4 | The verification of numerical simulation model

In this section, ABAQUS was used to simulate the uniaxial compressive strength test of sandstone to verify the numerical model. The rock specimen is cylindrical sandstone cores of 25 mm in diameter and 50 mm in length, and the mechanical properties are as follows: uniaxial compressive strength \(\sigma_c = 102.2\) MPa, uniaxial tensile strength \(\sigma_t = 4.6\) MPa, internal friction angle \(\phi = 41.0^\circ\), and hardness \(H = 847\) MPa. The physical and mechanical parameters used in the model are in Table 1. In the simulation, the degree of freedom of the specimen in the \(X\) and \(Y\) direction was constrained. The bottom of the rock sample was fixed completely, and a compressive displacement load of 5 mm was applied on the top of the rock sample along the \(Z\) direction.

Figure 6 shows the stress-strain curves obtained from the laboratory test and numerical simulation. Figure 7 shows the failure pattern of sandstone under laboratory test and numerical simulation conditions. As illustrated in Figures 6 and 7, the rock compressive strength obtained by numerical simulation was consistent with the laboratory test result. Moreover, the failure pattern of rock was also similar, a penetrating crack extended from the upper surface to the side of the rock sample, and the rock has an

![FIGURE 5 Yield surfaces of the linear D-P model](image)

![A) On the meridional plane](image)

![B) On the π plane.](image)

| TABLE 1 | Relevant material parameters used in simulation |
|---------|---------------------------------------------|
| Material | Density kg/m³ | Elastic modulus GPa | Poisson's ratio | Thermal conductivity W/(m °C) | Specific heat J/(kg °C) | Expansion coefficient °C⁻¹ |
| PCD     | 3510           | 890                | 0.07            | 543.0                        | 790                       | 2.5 × 10⁻⁶                 |
| WC-Co   | 15000          | 579                | 0.22            | 100.0                        | 230                       | 5.2 × 10⁻⁶                 |
| Rock    | 2700           | 27.8               | 0.19            | 3.5                          | 800                       | 52.0 × 10⁻⁶                |
obvious shear failure. The results indicate that simulation results are in good agreement with laboratory test results, which verifies the capability of the model to simulate rock fracture and stress-strain behavior.

4 | RESULTS AND DISCUSSION

4.1 | Rock-breaking process

In this section, a series of linear cutting simulations were conducted at different rock-breaking modes, including steady load cutting ($k_a = k_i = 0$), axial impact rock breaking ($k_a = 0.3, k_i = 0$), torsional impact rock breaking ($k_a = 0, k_i = 0.3$), and compound impact rock breaking ($k_a = k_i = 0.3$). In the simulation of impact rock-breaking modes, the impact frequency was set to 30 Hz, the impact duration was set to 0.1 ms, and the impact load loading curve was set to a sine curve, as shown in Figure 8.

MSE was usually used to evaluate the rock-breaking efficiency and performance. The concept of MSE was defined as the work required to remove a given volume of rock. The lower MSE, the higher the rock-breaking efficiency. MSE is calculated by the following equation:

\[
\text{MSE} = \frac{W}{V} = \frac{\sum_{i=1}^{n} F_{ci} \Delta x}{\sum_{i=1}^{n} A_i \Delta x}
\]  

where MSE represents mechanical specific energy (MPa). $W$ represents the total work consumed during rock-breaking process (J). $V$ is the broken volume of rock ($m^3$). $\Delta x$ is a given cutting stroke (m). $F_{ci}$ represents the average cutting force of cutter in $\Delta x$ (N). $A_i$ is the average cutting area in $\Delta x$ ($m^2$).

Figure 9 depicts the change curves of cutting force under different rock-breaking modes. During the rock-breaking process, the cutting force presents the periodic alternation of wave peaks and troughs. In a cutting stage, the cutting force increased gradually. The maximum cutting force was reached when the stress of rock comes the yield condition. Then, the broken rock elements separated from the rock body, the cutting force decreased rapidly to start the next cutting stage. As seen in the figure, the impact load application does not change the characteristics of periodic oscillation of the cutting force. The average cutting force is 250.5 N, 239.3 N, 234.7 N, and 230.8 N under steady load cutting, axial impact cutting, torsional impact cutting, and compound impact cutting modes. Compared with steady loading cutting, axial impact, and torsional impact, the cutting force under compound impact is reduced by 7.9%,
3.6%, and 1.7%, respectively. The results showed that the average cutting force of the cutter decreases after applying impact load and that of the compound impact mode is the smallest. Therefore, compared with the steady load cutting and the other rock-breaking modes, the compound impact load can effectively improve the stress state of the PDC cutter, which is conducive to reducing the bit wear and prolonging the service life.

Figure 10 shows that under the steady load cutting, axial impact, torsional impact, and compound impact rock-breaking modes, the broken volume increases while the MSE gradually decreases. Compared with conventional cutting, the broken volume of compound impact mode increased by 7.5%, while the MSE decreased by 12.3%. The simulation results show that the rock-breaking efficiency of the compound impact mode is the highest, which is beneficial to enhance the drilling efficiency and ROP.

As shown in Figure 11A-D, the cutting path below the cutter is relatively smooth in the rock-breaking process of steady load cutting and torsional impact modes. However, noticeable crushing pits can be observed on the cutting path in the axial impact and compound impact rock-breaking modes, mainly caused by repeated axial impact load. Besides, the size of cuttings produced during steady load cutting, axial impact, torsional impact, and compound impact cutting process gradually increased. There are apparent large chunk-like cuttings in torsional impact and compound impact cutting rock-breaking modes. This can be explained as follows. First, the axial

![Figure 9](image_url)
**Figure 9** Cutting force variations under different rock-breaking modes

![Figure 10](image_url)
**Figure 10** Broken volume and MSE under different rock-breaking modes
impact increases the penetration depth of the cutter, and the failure mode of rock changes from plastic failure to brittle failure. Second, the torsional impact makes the rock in front of the cutter more prone to brittle shear failure, resulting in large rock cuttings. Moreover, it is noteworthy that MSE shows the opposite trend with the size of the cuttings, decreasing with the size. This is due to the reduction of energy loss with the increase of cuttings size when breaking equal volume rock.35

4.2 Cutting temperature

Figure 12 shows the temperature changes curves of the cutter under different rock-breaking modes. It can be seen from the figure that the temperature change under different rock-breaking modes is similar. The temperature change processes consist of three stages: Stage I is the initial contact stage between cutter and rock, during which the cutter temperature rises rapidly; stage II is the establishment stage of stable cutting, in which the cutter temperature increases slowly over time; stage III is a stable cutting stage, at which time the cutter temperature appears to fluctuate relatively smoothly and periodically.

Moreover, the peak temperature of the cutter is different in the stable stage under different rock-breaking modes. The peak temperatures of the cutter are 65.69°C, 68.72°C, 68.13°C, and 69.07°C under steady load cutting, axial impact, torsional impact, and compound impact rock-breaking modes, respectively. It can be found that the cutter temperature in impact rock-breaking modes is higher than that of steady load cutting. The reasons why the cutter temperature increases under impact load are as follows: (a) Axial impact increases the instantaneous depth of cut, increasing the friction contact area, and intensifying the friction between the cutter and the rock. (b) Torsional impact increases the normal force and the slipping speed between the cutter and the rock, increasing the heat generated by the friction.
FIGURE 12  Temperature variation of PDC cutter under different rock-breaking modes

FIGURE 13  Temperature change during rock-breaking process under compound impact
Figure 13 shows the temperature nephogram in the rock-breaking process of compound impact. The temperature increases gradually due to extrusion and friction between the cutter and rock during the cutting process. Subsequently, the strain of the rock continuously accumulated and began to deform, and the energy in the rock is released gradually, as shown in Figure 13A,B. Then, the cuttings are separated from the rock body due to the crack propagates to the free surface. The contact area between the cutter and the rock is reduced, and the heat generated is reduced. At the same time, the dissipation of the cuttings will also take away part of the energy, resulting in the temperature reduction of the cutter, as shown in Figure 13C,D. As a result, the discontinuous cutting in the rock-breaking process is the main reason for the periodic fluctuation of cutter temperature.

### 4.3 Effects of impact parameters on rock-breaking performance

#### 4.3.1 Effect of axial impact load amplitude

During the compound impact drilling, shock waves in the axial direction were applied to assist rock breaking, and the axial dynamic load amplitude would directly affect the rock-breaking efficiency. In this section, the effects of axial impact load amplitude on the rock-breaking performance and cutting temperature in compound impact drilling were analyzed. The parameters are set as follows. The ratio of torsional dynamic load to static load is set to 0.3. The rock temperature is set to 25°C. The ratio of axial dynamic load to static load is set to 0.1, 0.2, 0.3, 0.4, and 0.5, respectively.

Figure 14 shows the rock broken volume and MSE of different $k_a$ values. It can be seen that the axial dynamic load has little effect on the broken volume. However, the MSE increases gradually with the ratio of axial dynamic load to static load, which shows that increasing axial impact load amplitude is not conducive to the improvement of rock-breaking efficiency in compound impact drilling. This can be explained as follows: Due to the extrusion action of the cutter under axial impact, when the rock at the front and bottom of the cutter reaches the failure strength, the rock is broken to form debris. The plastic deformation of the inner rock is gradually severe with the further increased axial dynamic load, that is, more rock deformation and heat accumulation, rather than more rock fracture and damage. Figure 15 shows the cutter temperature of different $k_a$ values. It can be seen that the cutter temperature increases with the ratio of axial dynamic load to static load. The reason is that with the increase of the axial impact load amplitude, the instantaneous depth of cut and sliding speed of the cutter increase gradually, increasing the friction heat and the cutter temperature. The simulation results show that the amplitude of axial impact load should not be too large, which is consistent with the conclusion of Zhu et al. 37

#### 4.3.2 Effect of torsional impact load amplitude

In this section, we exerted the torsional pulse loads with different amplitudes on the cutter. Keep the other parameters constant, the ratio of torsional dynamic load to static load is set to 0.1, 0.2, 0.3, 0.4, and 0.5, respectively. Figure 16 demonstrates the effect of the torsional impact load amplitude on the broken volume and MSE. Figure 17...
presents the effect of the torsional impact load amplitude on the cutter temperature.

Figure 16 shows that the higher the dynamic torsional load, the larger the rock broken volume, while the MSE decreases first and then increases. The results indicate that increasing the torsional impact load amplitude is helpful to rock fragmentation. And the MSE reaches the minimum value at 0.3, which suggests that the rock-breaking efficiency is relatively high at this torsional load amplitude. As shown in Figure 17, the cutter temperature increases linearly with the ratio of torsional dynamic load to static load. The reason is that with the increase of the torsional impact load amplitude, the instantaneous normal force and sliding speed of the cutter increase gradually, increasing the heat generated by friction and the cutter temperature. This is consistent with the conclusions of Zhang et al.3

### 4.3.3 Effect of impact frequency

With the increase of the impact frequency, the input energy per unit time exerts on the bit increases accordingly. In this section, other impact parameters were fixed, and the impact frequency was set to 10 Hz, 20 Hz, 30 Hz, 40 Hz, and 50 Hz, respectively. The effects of frequency on rock-breaking performance and cutting temperature were analyzed, as shown in Figures 18 and 19.

Figure 18 shows that the rock broken volume increases with the increases in impact frequency, which indicates that increasing the impact frequency is helpful to rock fragmentation. However, the MSE first decreases and then increases with the frequency, suggesting that the impact frequency has an optimal range under compound impact. The rock-breaking efficiency is higher when the impact frequency is 30 Hz. As illustrated in Figure 19, as the
impact frequency increase, the cutter temperature gradually decreases. A possible reason for the above phenomenon is that when the impact frequency is high, the speed of rock failure and escape is accelerated, which shortens the contact time between the rock and the cutter, reducing the friction heat transferred to the cutter.

4.3.4 | Effect of impact load waveforms

Different shapes of the impact hammer can generate dynamic load with different impact load waveforms, which will directly affect the rock-breaking efficiency. It is necessary to study the effects of the waveform on the rock-breaking performance and cutting temperature. In this section, the impact load amplitude and frequency were kept unchanged, and the shapes of the waveform were changed among triangular wave, sine wave, and square wave, as defined in Figure 8. The change of broken volume, MSE, and cutter temperature under different waveforms is shown in Figures 20 and 21.

As shown in Figure 20, the broken volume under the condition of a square wave is the largest, while that of the sinusoidal waveform is the middle, and that of the triangular waveform is the smallest. There is a positive correlation between rock broken volume and the input energy. However, the MSE under the condition of a triangular waveform is the largest, while that of the square waveform is the middle, and that of the sinusoidal waveform is the smallest. The results indicate that the sinusoidal waveform generated by the impact hammer has the highest rock-breaking efficiency. This is consistent with the conclusions of Song et al. Comparing Figures 20 and 21, we can find that the effects of different waveforms on the cutter temperature are consistent with its effects on the rock broken volume. The main reason is that the instantaneous depth of cut and slip speed of the cutter will increase correspondingly under the condition of significant input energy. The energy generated by the friction between the cutter and the rock increases, increasing cutter temperature.

5 | STRUCTURE DESIGN AND TEST OF COMPOUND PERCUSSIVE DRILLING TOOL

Based on the above analysis, a novel compound percussive drilling tool was designed, as shown in Figure 22. The mechanism of this tool is as follows: A part of the high-pressure fluid alternately enters the upper and the lower cavities, making the axial percussive hammer move up and down, as shown in Figure 22A. At the same time, the other part of the high-pressure fluid alternately enters the left and the right cavities, pushing the torsional percussive hammer swing left and right, as shown in Figure 22B. Finally, in the process of axial and torsional hammers impacting the anvil, the periodic axial and torsional dynamic load are generated, respectively, forming a compound percussive effect on the bit. The structure diagrams of the axial and torsional hammers are shown in Figure 22C. To improve the service life of the compound percussive drilling tool, the 42CrMo steel is employed in the tool components. 42CrMo steel is one of the representatively high strength steel, and the mechanical parameters are list in Table 2. The simulation results showed that the pulse load generated by axial hammer is an approximately square wave, while the torsional hammer could generate a sine wave, as shown in Figure 23. The laboratory test results suggested that when the flow rate reached 34.0 L/s, the tool’s pressure drop was 3.41 MPa, and the impact frequency could reach 28.1 Hz, as shown in Figure 24.
Besides, the test results also verified the rationality of the tool structure and provided a theoretical basis for the follow-up field application.

The field experiment of compound percussive drilling was conducted in a 3335 m deep test well in Xinjiang, China. The lithology of the drilling section is medium-hard rock. Under the same drilling parameters, the average ROP of the 307 m test well section is 5.3 m/h, while that of the adjacent well is 4.2 m/h. The ROP is increased by 26.2% after the application of compound percussive drilling tool. After drilling operation, the PDC bit is still in good condition, as shown in Figure 25, each blade has only smooth wear and slightly broken cutter, and the cutter has no thermal wear. The drilling results show that the compound percussive drilling tool can not only improve the rock-breaking efficiency, but also reduce the premature wear of the PDC bit.
failure of the PDC bit and prolong its service life. The field test results further verify the simulation results.

6 | CONCLUSIONS

In order to better understand the rock-breaking mechanism of compound percussion drilling, a finite element analysis of the rock-breaking process and cutting temperature with a single cutter under compound impact was conducted. The cutting force, MSE, and rock failure mode under different rock-breaking modes were analyzed. The effects of the dynamic load amplitude, impact frequency, and waveforms on the rock-breaking performance and cutting temperature of compound percussive drilling were studied. The following conclusions were obtained:

1. Among the steady load cutting, axial impact, torsional impact, and compound impact rock-breaking modes, the rock broken volume is the largest under compound impact load, while the average cutting force and MSE are the smallest. Compared with steady load cutting, the rock broken volume under compound impact increased by 7.5%, and MSE decreased by 12.3%, which is expected to increase the ROP and prolong the services life of PDC bit in hard rock drilling.

2. With the increases of axial impact load amplitude, the MSE of compound impact drilling increases, and the amplitude of axial impact load should not be too large. With the increase in torsional impact load amplitude and impact frequency, the broken volume increases, but the MSE decreases first and then increases. The optimal torsional static load ratio is 0.3, and the optimal impact frequency is 30 Hz. For the three pulse waveforms—sine, triangle, and square in this paper, the rock-breaking efficiency under the condition of sine waveform is the largest when the dynamic amplitude of the pulse force is fixed.

3. Compared with steady load cutting, the cutting temperature of the compound impact mode is higher. The cutting temperature rises with the dynamic load amplitude, and it decreases with an increase in impact frequency. The cutting temperature under the condition of square waveform is the highest when the dynamic amplitude of the pulse force is fixed.

4. A novel compound percussive drilling tool was designed based on the analysis of the rock-breaking mechanism under compound impact load. The axial hammer could generate a square wave, while the torsional hammer could generate a sine wave. The field experiment results show that the tool can effectively improve the rock-breaking efficiency of the PDC bit.

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