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Numerical Simulation of Rock Fragmentation under PDC Cutter Assisted by Water Jet based on H-J-C Model

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Abstract

In the industry of oil and gas exploration and development, rock fragmentation technology of mechanical cutter assisted by water jet is promising for improving drilling speed and reducing drilling cost. However, the highly complex mechanical properties of rocks limit the research progress of this technology. The nonlinear mechanical behavior of rock under impact load can be well characterized by H-J-C model. This paper takes sandstone as the research object, deduced the dynamic material parameters of J-H-C model of sandstone according to the mechanical parameters of sandstone. And to investigate the rock fragmenting performance under PDC cutter assisted by water jet, a numerical model based on the finite element theory is also established in the paper. Through the above model, the paper analyzes damage evolution characteristics, rock fragmenting mechanism, the efficiency of rock fragmentation under different water jet speed in the process of PDC cutter fragmenting rock assisted by water jet. The results show that water jet-assisted cutting technique in the efficiency of rock fragmentation and cutting force of PDC is superior to pure PDC cutter cutting technology; in this paper the test data, the better the higher the speed of water jet fragmenting rock efficiency. The analysis data in this paper will provide important reference for application of water jet-assisted fragmenting rock in stratum of hard rock.

Keywords

Water Jet; PDC Cutter; H-J-C Model; Rock Fragmentation.

1. Introduction

In the oil and gas exploitation, PDC bit is one of the important equipment for drilling. The performance of PDC bit also has an important impact on the cost and efficiency of oil and gas resources development. At present, the footage of PDC bit worldwide has accounted for more than 90% of the total footage of the bit. However, PDC bit is mainly suitable for medium and hard stratums. When the bit encounters deep hard stratums, it is difficult to penetrate rock for the drill cutter, easy to wear and fracture [1]. With the development of exploration and development of oil and gas resources, the drillability of rocks is getting worse and worse, and the mechanical drilling rate is getting lower and lower. Therefore, the rock fragmenting mode also develops from single fragmenting to composite cutting fragmenting [2].

Water jet technology has the advantages of high energy utilization, low temperature cleaning and shaped energy impact. It is widely used in the fields of material cutting, surface treatment, tunnel construction and mineral mining. In 1985, the rock fragmenting test of water jet assisted excavator was carried out in Egoclaff Mine in the United Kingdom. The results showed that technology of the water jet-assisted fragmenting rock increased the rock fragmenting efficiency by 75% and reduced the specific energy consumption by 42%. Many tests and theoretical studies have shown that jet assisted mechanical tools fragmenting rock can improve the efficiency of rock fragmenting and

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reduce energy consumption. At present, the technology of jet assisted rock fragmenting is mainly used in the fields of coal mining and tunneling, but is seldom used in oil and gas exploration and development. The rock fragmenting technology of water jet assisted PDC cutter is constantly mentioned in order to achieve the aim of drilling and acceleration.

The technology of water jet assisted PDC cutter fragmenting rock by is to make use of the efficient cutting ability of the water jet to produce pre-damage to the rock, and then scrape the rock through the PDC cutter to form rock fragmentation. Due to the formation of damage to the rock in advance, local cracks are generated, and the rock strength and other mechanical properties of the damaged parts are reduced, which is convenient for PDC cutter to remove large rocks in volume, and can also improve the force of the tool to improve the life of the tool. The rock fragmenting by water jet and the rock fragmenting by PDC cutter have been studied by many people. Huang Fei and Xue Yongzhi et al. revealed the stress wave propagation mechanism and microscopic damage evolution law in rock during the process of water jet fragmenting through experimental and theoretical research [3-4]. Wang Hongxiang conducted a laboratory experiment on the influence of rock strength, cutting head type and water pressure on water-jet assisted fragmenting rock, providing a theoretical reference for the design of jet assisted cutting head [5]. Hu Yang studied the rock fragmenting ability of slurry jet-pick structure combination from aspects of jet parameters, pick life and slurry flow field, etc. The research results showed that slurry jet-pick structure combination rock fragmenting technology could significantly reduce the force of pick and greatly improve the working life of pick [6]. This paper takes Nanchong sandstone as the research object to investigate the rock fragmentation ability of water jet assisted PDC cutter.

2. Constitutive model of rock

Nanchong sandstone of Reference [7] is selected as the research object, and mechanical parameters of the rock are shown in Table 1 below.

Table 1. Mechanical parameters of Nanchong sandstone of Reference [7]

Density/kg/m^3	Poisson's ratio	Uniaxial compressive strength /MPa	Tensile strength /MPa	Modulus of elasticity /GPa
2400	0.111	50.56	2.836	5.22

The rock is highly nonlinear under impact of high-pressure water jet. In this paper, H-J-C model is selected to simulate the mechanical behavior of rock under the action of PDC cutter assisted by water jet. H-J-C model was originally a constitutive model of concrete, and later it was often used to describe the nonlinear, high strain rate and large deformation problems of rock-like materials under the loading of high-speed impact, penetration and explosion [8-9].H-J-C model mainly includes three parts: strength model, damage model and constitutive equation, as shown in Fig. (1).

Strength model: rock strength is a function of pressure, strain rate, and damage, is expressed by Eq. (1):

$$\sigma^* = [A(1-D) + BP^{*N}](1 + Cln\dot{\varepsilon}^*) \tag{1}$$

Where $\sigma^* = \sigma/f_c'$ is the normalized equivalent stress, σ is the actual equivalent stress, and f' is the quasi-static uniaxial compressive strength. $P^* = P/f_c'$ is the normalized pressure; P is hydrostatic pressure; $\dot{\varepsilon}^* = \dot{\varepsilon}/\dot{\varepsilon_0}$, $\dot{\varepsilon}^*$ is the dimensionless strain rate, $\dot{\varepsilon}$ is the actual strain rate; $\dot{\varepsilon_0}$ is the reference strain rate. D is the damage parameter, which is obtained by accumulating the equivalent plastic strain and the plastic volume strain.

Damage model: Damage of material is based on the accumulation of equivalent plastic strain and plastic volumetric strain. When damage factor D=1, it indicates complete failure. When ε_{fmin} is reached, the material fails, as shown in Fig. (2). The damage model is expressed as Eq. (2):

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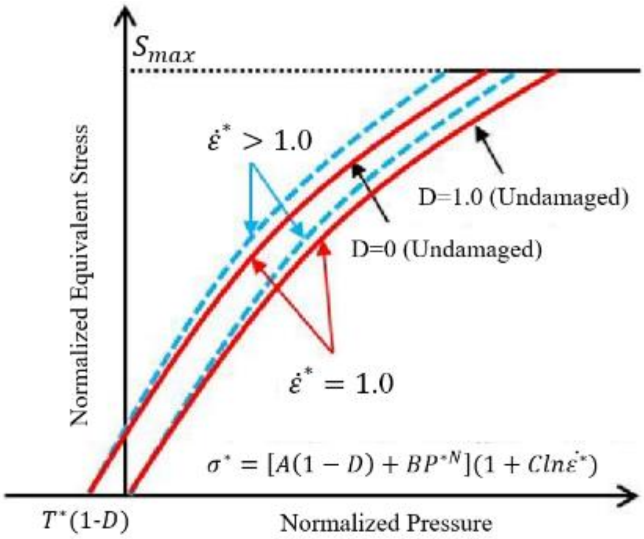
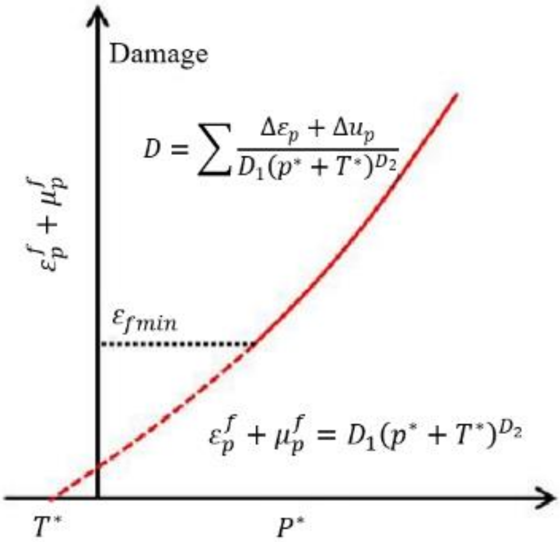
$$D = \sum \frac{\Delta\varepsilon_p + \Delta\mu_p}{D_1(p^* + T^*)^{D_2}} \quad (0 \le D \le 1) \tag{2}$$

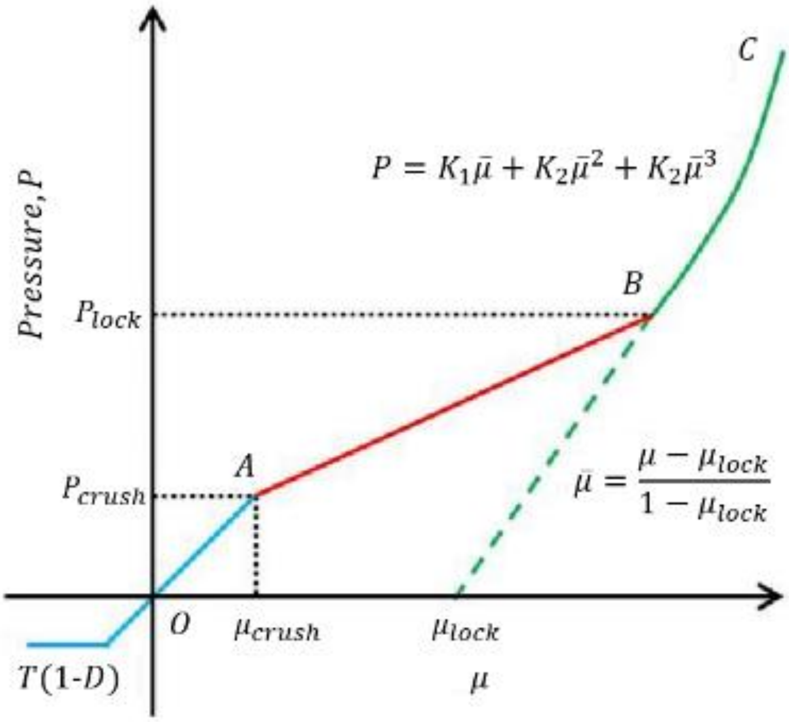
Where $\Delta\varepsilon_p$ is the equivalent plastic strain increment; Δu_p is the equivalent volume strain increment; $(P^* + T^*)^{D_2}$ is the plastic strain at the time of material fracture under normal pressure P; T^* is the normalized maximum tensile hydrostatic pressure that the material can sustain; D_1 and D_2 are the damage constants.



(a) Strength model



(b) Damage model



(c) Constitutive equation

Fig. 1 H-J-C model

Constitutive equation: constitutive equation describes the relationship between hydrostatic pressure and volumetric strain of rock under hydrostatic load. Rock deformation under load shows three stages.

Stage 1: Linear elasticity stage. When $P<P_{crush}$, rock deformation is in elastic stage. u_{crush} and P_{crush} are respectively the volumetric strain and hydrostatic pressure of the material when it reaches the elastic limit. Bulk modulus of elasticity is calculated by Eq. (3):

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$$K_{elastic} = \frac{P_{elastic}}{u_{elastic}} \tag{3}$$

Rock shear modulus G and volume modulus K can be determined according to the following formula (4) and (5):

$$G = \frac{E}{2(1+v)} \tag{4}$$

$$K = \frac{E}{3(1-2v)} \tag{5}$$

Stage 2: plastic stage. When $P_{crush} < P < P_{lock}$, the empty holes and gaps in the rock body are gradually compressed, and plastic volume deformation occurs in the rock body.

$$P = [(1-F)\cdot K_{elastic} + f \cdot K_1]\cdot \mu \tag{6}$$

$$F = \frac{\mu - \mu_{crush}}{\mu_{lock} - \mu_{crush}} \tag{7}$$

Stage 3: dense stage. When $P > P_{lock}$, the cavities and gaps in the rock are completely compacted.

$$P = K_1\bar{\mu} + K_2\bar{\mu}^2 + K_2\bar{\mu}^3 \tag{8}$$

$$\bar{\mu} = \frac{\mu - \mu_{lock}}{1 - \mu_{lock}} \tag{9}$$

According to the Hugoniot shock wave data in 1993 literature [9] and literature [10], it can be obtained that K_1=85GPa, K_2=-171GPa and K_3=208GPa.

In summary, the H-J-C model parameters of rock are shown in the following table. The parameters of H-J-C model are shown in Table 2 below.

Table 2. H-J-C model parameters of rock

ρ/kg/m^3	G/GPa	Fc/MPa	A	B	C	N	K1/GPa	K2/GPa	K3/GPa
2400	2.350	50.56	0.79	0.8	0.0001	1.00	85	-171	208
T/MPa	Pc	μc	Pl	μl	Efmin	Smax	ε	D1	D2
2.836	16.855	0.00756	800	0.1	0.005	7.0	0.00001	0.04	1.0

3. Verification of rock numerical model

The numerical simulation of uniaxial compression test is carried out by the above rock model. The numerical model of uniaxial compression is shown in Fig. (2). There are 308100 rock elements, and the rock model is a standard sample of cylinder rock sample with a diameter of 50mm and a height of 100mm. In the finite element analysis, the element type of rock is 8-node hexahedral element, and the upper and lower plates are rigid body materials. The upper plates are loaded at 1.3mm/s. The element stress-strain curve of the model and the failure result of rock are shown in Fig. 2. Elastic modulus E=5.260GPa, Poisson's ratio μ=0.101, and uniaxial tensile strength Fc=50.1MPa can be calculated from the stress-strain curve of the model. The parameters are approximately equal to those of the rock mechanics parameters mentioned above. Therefore, the model can be used to characterize the rock mechanics parameters such as compressive strength, Poisson's ratio, elastic modulus and so on.

Besides, Brazil splitting test is carried out to simulate the rock model, and the contact force between the plate and the rock is taken. The results are shown in Fig. 3. The maximum contact force is 2.15×10^4N, so the calculated tensile strength is 2.739MPa, which is close to the tensile strength 2.836MPa of Nanchong sandstone in literature [7]. Therefore, this model parameter can be used to characterize the tensile strength of this rock.

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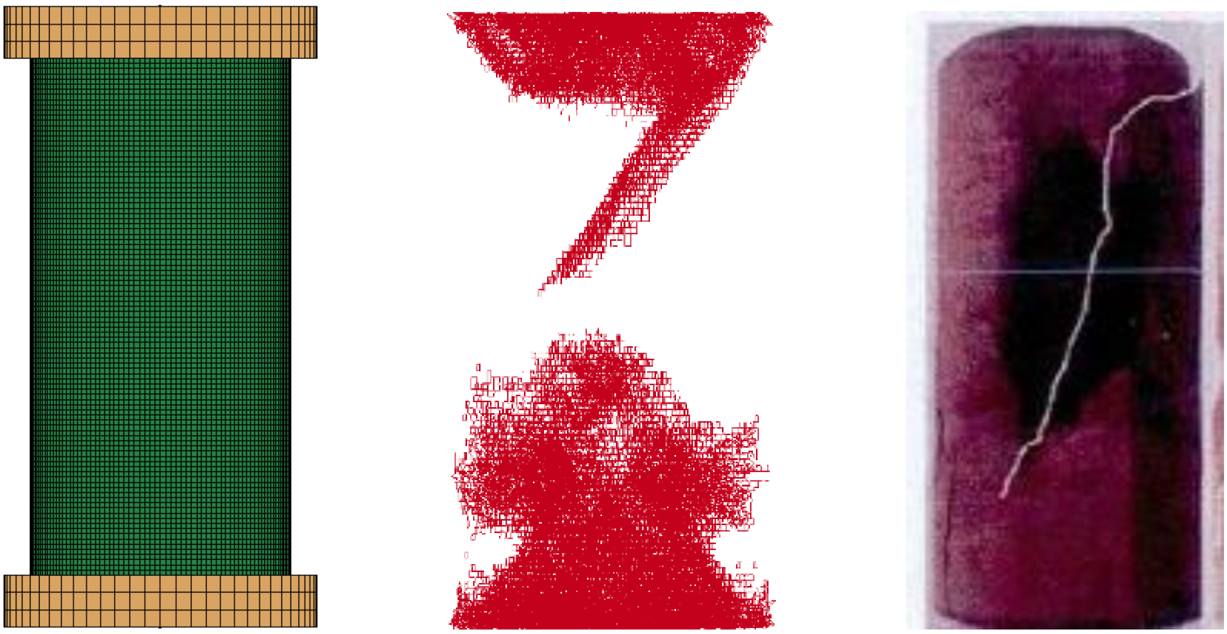
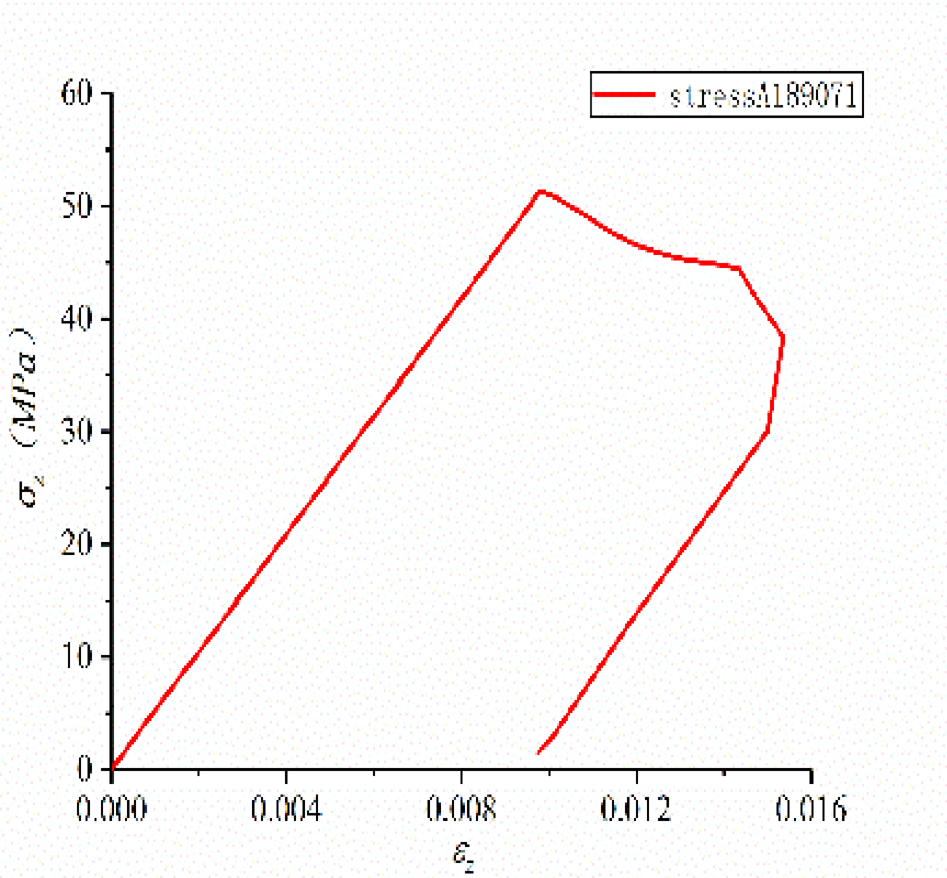


(a)model (b)failure distribution of simulation (c)the experimental results of sandstone



(d) stress-strain curve

Fig. 2 Simulation results of uniaxial compression experiment

To sum up, the parameters of the H-J-C model used in this paper have a small deviation with those measured in the experiment in the literature[7], which can well characterize the mechanical properties of the rock. The parameter of H-J-C model can be used as the water jet to fragment rock in the following study, which can ensure the accuracy of the model in the later study.

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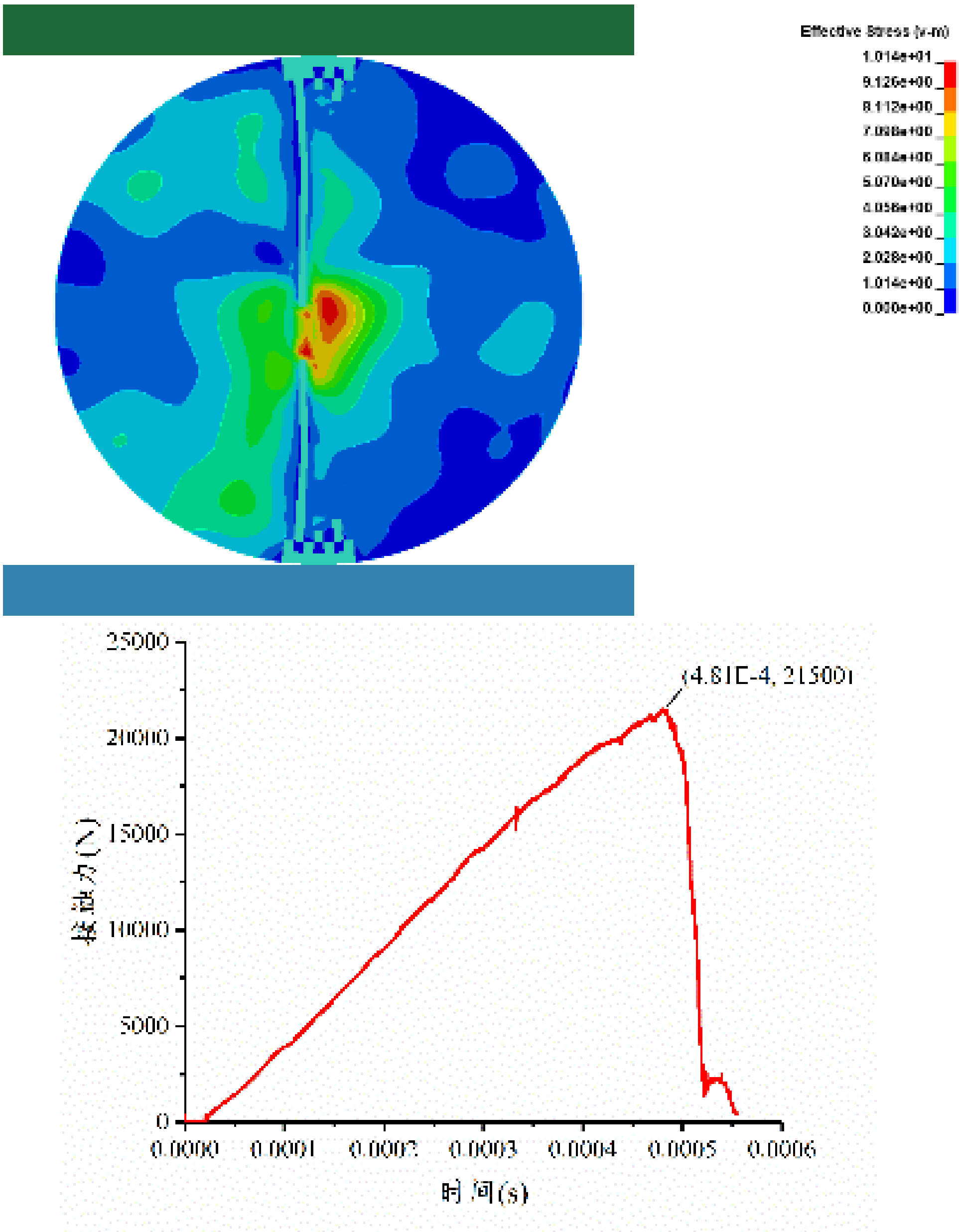

Fig. 3 The results

4. Numerical Simulation of Rock fragmenting under PDC cutter Assisted by Water Jet

4.1 Numerical model of Rock fragmenting under PDC cutter Assisted by Water Jet

The rock-fragmenting process of water jet impact is a nonlinear dynamic coupling problem between high-speed fluid impact on solid. In order to approach the real process and simplify the model design, the rock is assumed to be an isotropic continuum, and the influence of temperature and bottom hole flow field on rock and water jet is not considered. The failed rock elements are immediately removed. The water jet impinges on the rock at a constant speed, and the PDC cutter scrape the rock at a constant speed. In the numerical simulation, square rock blocks are used as rock materials to carry out numerical simulation of jet perforation on the rock center, and the geometric model is shown in Fig. 4.The size of the rock is set as 25mm×25mm×10mm, the diameter of the water jet is 2mm, the distance between the water jet and the rock is 2mm, the angle of the PDC cutter is 20°, the diameter of the cutter is 8mm, and the speed of the cutter is 2.5m/s. The water jet velocity is 250m/s, 350m/s and 450m/s for simulation. The unit is g-cm-μs.

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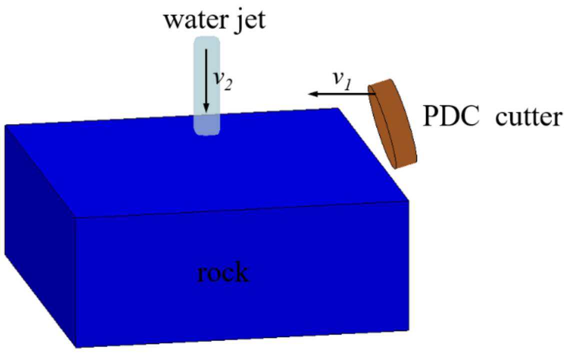

Fig. 4 Geometric model diagram of rock fragmentation under PDC cutter assisted by water jet

4.2 Numerical simulation results and analysis

4.2.1 Damage evolution distribution of rock

The failure of rock under external force is the macro representation of the accumulation of meso-damage inside rock. Exploring the evolution distribution of the damage inside rock is an effective approach to reveal the mechanism of rock fragmenting. The damage variable of H-J-C model is obtained by the accumulation of equivalent plastic strain and plastic volumetric strain, which can represent the damage of rock caused by volume deformation and plastic deformation. In this section, rocks under the action of water jet assisted PDC cutter scraping at a water speed of 250m/s are taken as an example. The distribution of rock damage is shown in Fig. 5.

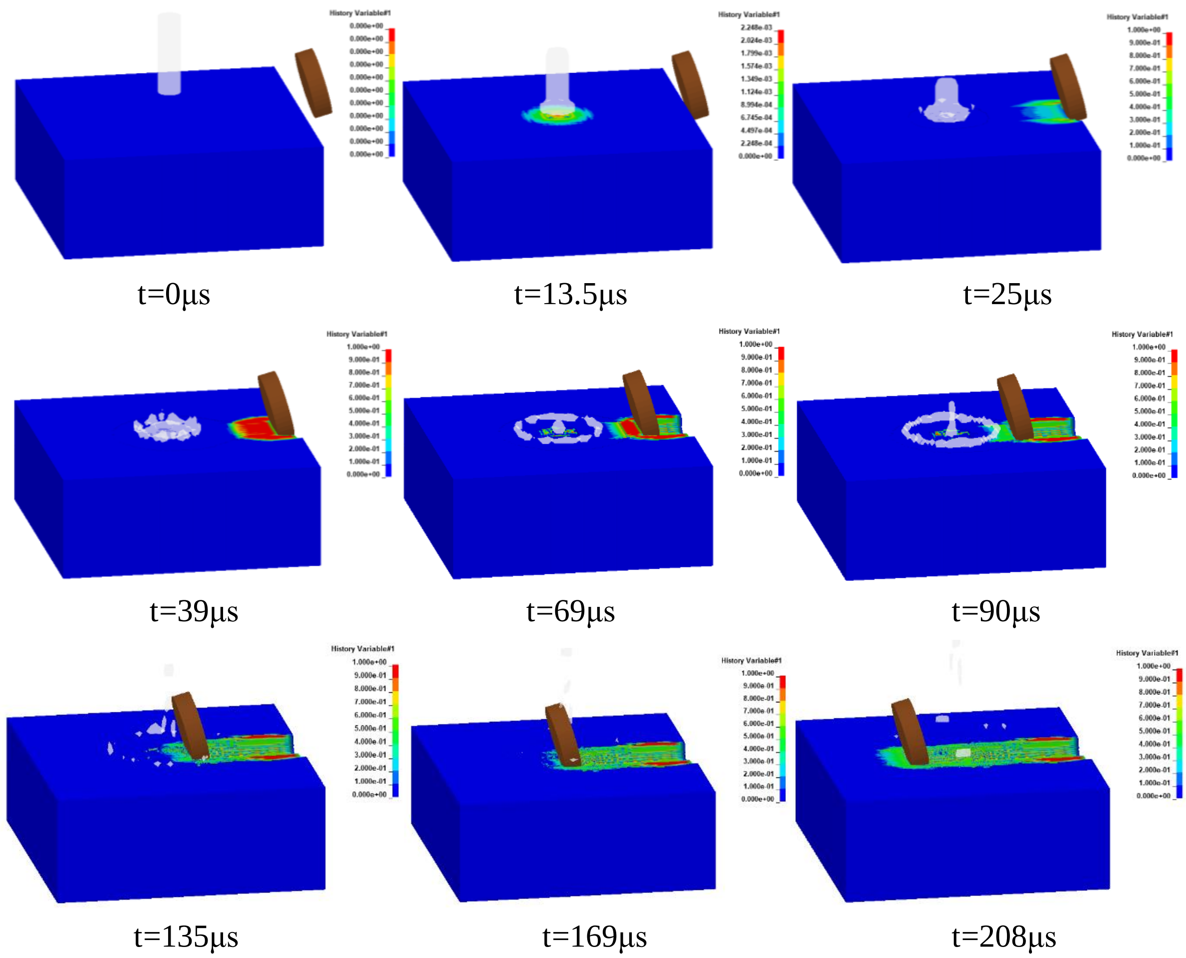

Fig. 5 Damage distribution of rock under water jet assisted PDC cutter

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The rock fragmenting process of water jet assisted PDC cutter can shows four stages:

1. The region of rock fragmentation under water jet is in the center of the jet; PDC cutter scrape the rocks outside the jet area, and the rocks in these two processes will suffer different degrees of damage under the two actions respectively.

2. A groove appear in the surface of rock under PDC cutter, and residual damage is left on the surface of the groove. There is a relatively concentrated peak damage accumulation phenomenon on the edge of the groove, which is macroscopic crack.

3. When PDC cutter are scraping and cutting area of rock acted by water jet, the rock surface showed point-like peak damage. It is the result of first surface failure and fragmentation caused by water jet in the process of impact on the rock, and second failure and damage caused by stress concentration under PDC cutter scraping and cutting.

4. When the PDC cutter leaves the core area of the jet, the rock shows uniform damage.

4.2.2 Analysis of rock fragmenting effect

Under the different velocity of the water jet, the total volume fraction of the rock body model was taken as the scalar of the failure volume, and the interface contact force between PDC cutter and rock is taken as the cutting force of PDC cutter. The results are shown in Fig. 6 and Fig. 7.

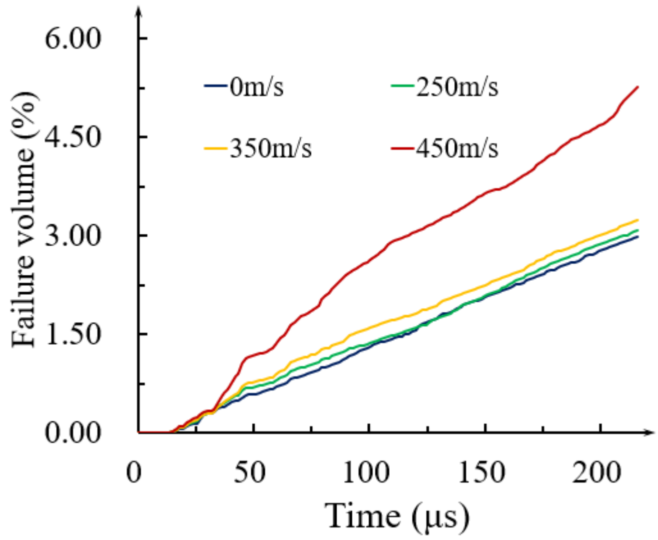

Fig. 6 Failure volume of water jet assisted PDC cutter fragmenting rock

As can be seen from Fig. 6, when the water jet velocity is 0m/s, the rock fragmentation volume is the smallest. When the water jet velocity is 450m/s, the rock fragmentation volume is largest. The rock fragmentation volume of water jet assisted PDC cutter is positively correlated with the water jet velocity. Besides, the increase of rock fragmentation volume is small under the velocity of 250m/s~350m/s, the increase of rock fragmentation volume is more obvious under 450m/s, and the rock fragmentation effect is better under this condition.

4.2.3 Cutting force analysis of PDC cutter

Fig. 7 shows the cutting forces at different speeds, and the average cutting forces are shown in Table 3. Taking the calculated results at a velocity of 0m/s as a reference, the cutting forces of PDC cutter differently performance outside the jet impact area and in the center of the jet area. The cutting force of PDC cutter at different speeds from PDC to 100μs is almost the same as that at zero. At 100μs to 150μs, the cutting force is reduced compared with the previous stage. The cutting force increases at v_2 =250m/s and v_3 =350m/s from 130μs to 150μs. This is because the cutting position of PDC cutter has reached the boundary position of the core action of water jet. The water jet offsets part of the cutting effect of cutter, resulting in an increase in the cutting force at this stage. Generally, the cutting force is within a reasonable range. From 150μs to 200μs, the cutting force of PDC cutter changed greatly, because the water jet with different speeds had different degrees of failure on the rock in advance. The effect of water jet assisted PDC cutter cutting rock was concentrated in this stage, and the greater the water jet velocity was, the smaller the cutting force of PDC cutter was.

Table 3. The average cutting force of rock fragmentation PDC cutter assisted by water jet

Velocity(m/s)	0	250	350	450
cutting force(kN)	1.30	1.20	1.13	0.675

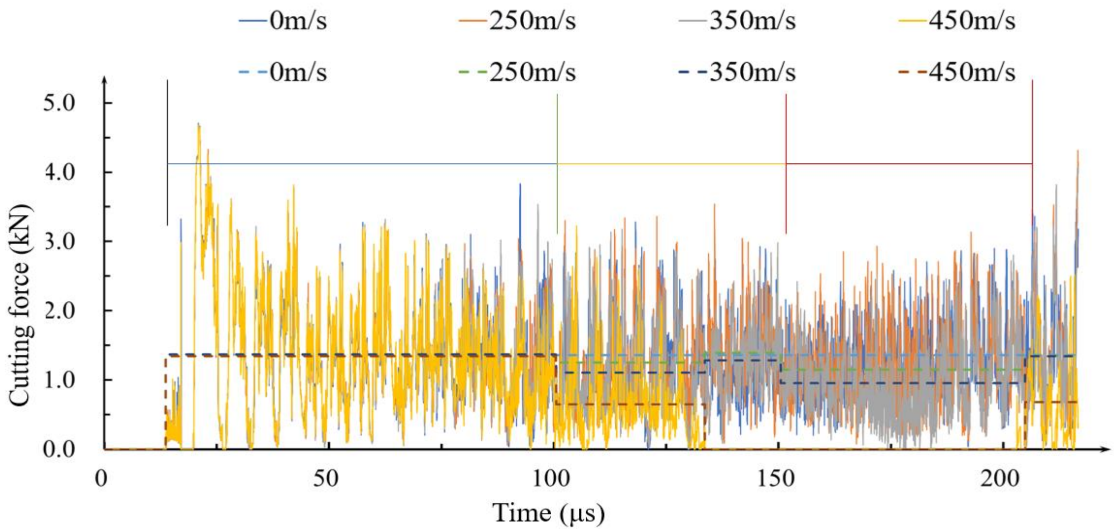

Fig. 7 The cutting force curve of rock fragmentation PDC cutter assisted by water jet

5. Conclusion

(1) Based on the mechanical parameters of the rock, the paper deduces the dynamic parameters of the H-J-C model applicable to the Nanchong sandstone, and the verification results were highly consistent with previous experimental results.

(2) The paper establishes the numerical simulation model of water jet assisted PDC cutter cutting based on display dynamics platform.

(3) The numerical results show that the rock fragmenting effect is positively correlated with the water velocity. The rock fragmenting effect and cutting force of the jet-assisted PDC cutter cutting technology are significantly better than that of the simple PDC cutter cutting technology.

The rock fragmentation model of water jet assisted PDC cutter is established in this paper. The numerical simulation analysis under different speed of water jet fragmenting rock volume, and the cutting force of PDC cutter for rock fragmentation effect analysis are carried out. The results show that water jet can improve the efficiency of rock fragmentation and reduce the cutting force of PDC cutter, can be a solution to improve the drilling speed of in-depth study.

Acknowledgments

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References

[1] LIU Weiji,ZENG Yijin,ZHU Xiaohua. Mechanism of rock breaking under composite and torsional impact cutting[J]. Journal of China University of Petroleum(Edition of Natural Science) ,2020,44(3): 74-80

ISSN: 2414-1895 DOI: 10.6919/ICJE.202104_7(4).0004

[2] Zhu Xiaohua, Liu Weiji, A coupled thermo and poro-elastoplasticity analysis of stress distribution in bottom-hole rocks during drilling[J]. Journal of China University of Petroleum (Edition of Natural Science), 2016, 40(5): 72-78.

[3] Huang Fei. On the Transient Dynamics of Water Jet Impinging Target and the Mechanism of Water Jet Breaking Rock [D]. 2016

[4] Xue Yongzhi. Study on the Inducement and Distribution of Damage in Coal Impacted by High Pressure Water Jets[D].2018

[5] Jiang Hongxiang. Study on Rock Fragmentation Performance of High-pressure Water-jets Cutting Head and Its Dynamics [D]. 2015

[6] Hu Yang. Research on Rock Breaking Performance of Abrasive Slurry Jet and Pick[D].2019

[7] Liao Feilong. Research on the damage law of rock-breaking process by PDC cutter[D].2014

[8] LS-DYNA keyword user'manual[Z]. Version 971, Livermore Software Technology Corporation, 2007

[9] T. J. Holmquist, G. R. Johnson, W. H. Cook. A computational constitutive model for concrete subjected to large strains, high strain rates and high pressures[J]. High Strain Rates and High Pressures, 1993,1-10.

[10] Xiao-feng WANG, Biao WU, Jing-bo LIU. Expermental research on equation of state of granite at high pressure [J]. Engineering Mechanics, 2020, 37(S): 237-241.