Experimental Study of Prefabricated Crack Propagation in Coal Briquettes under the Action of a CO₂ Gas Explosion

Kang Wang,* Hongyu Pan,* and Tianjun Zhang

ABSTRACT: CO₂ deep-hole presplit explosions are an important technology for enhancing gas drainage in low-permeability coal seams. In the process of a CO₂ gas explosion, the initial burst crack generated by the shock wave expands the crack tip under the splitting action of high-pressure CO₂ gas. To explore the effects of CO₂ gas explosions on crack tips, we constructed an analytical model of gas pressure attenuation at different positions based on fluid motion equations, proposed equations for crack opening and growth rates, and inverted the energy field of the whole process of CO₂ blasting. We used a test platform for the independent development of CO₂ gas explosions under experimental conditions of 1 MPa axial pressure and 2 MPa CO₂ gas pressure and a VIC-3D measurement system. We conducted the gas explosion experiments on prefabricated cracked samples with a crack length of 10 mm and width of 0.2 mm to analyze the dynamic response of the crack tip. The results showed that there were three stages in the propagation of a prefabricated crack under the action of a CO₂ gas explosion. The first stage, from 0 to 290 ms, included energy storage at the crack tip and a maximum opening rate increment of 0.0043 m/s. The second stage, from 291 to 295 ms, was rapid crack propagation with maximum opening rate increment and propagation rates of 0.1865 and 5.35 m/s, respectively. In the third stage, from 296 to 309 ms, the crack tip propagated slowly, the maximum opening rate increment and propagation rates were 0.0969 and 5.81 m/s, respectively, and the crack arrest coordinates were 4.57 and 35.28 mm. The experimental study verified the accuracy of the calculation model, proved that CO₂ gas promotes the growth of crack tips, explained the spatiotemporal evolution mechanism of the CO₂ explosion process, and provided experimental support for subsequent research related to explosions.

1. INTRODUCTION

Coal is the main energy source of China. With the continuous increase in mine depths, the pressure increases on coal seams, and the permeability of coal seams decreases. Therefore, research on antirefracture technology for coal seams is essential.¹ To increase the permeability of coal seams, domestic and foreign researchers have conducted many studies and achieved some results, such as hydraulic fracturing,² high-energy gas fracturing,³ and deep-hole cumulative explosions.⁴ However, these technologies have limitations; for example, the cost is high, the project size is large, or safety needs to be improved. CO₂ gas explosion antirefracturing technology has the advantages of high efficiency and safety, storage of greenhouse gases, and displacement of coalbed methane. Meanwhile, the explosion process avoids the waste of water resources, and the low explosion temperature ensures safety in the mining field by avoiding the collapse of coalbeds and dust caused by explosions of traditional gunpowder.⁵ Unlike N₂ fracturing and high-energy gas fracturing technologies, CO₂ gas reacts and combines with the mineral composition of the reservoir and has stronger displacement and splitting capabilities that improve the antirefracture effect of the explosion.⁶,⁷ thus, the CO₂ technology has received extensive attention from the industry in recent years.⁸

Many researchers have studied the gas explosion process based on the continuous medium and explosion gas quasi-static load hypotheses. Many studies have shown that the combination of stress wave and explosion gas loads can lead to coal rock cracks.⁹–¹¹ However, research on CO₂ explosions has focused on the damaging effects of stress waves on coal rock masses.¹² Sun¹³,¹⁴ studied the number and length of cracks under different initial stress conditions. Cai¹⁵ and Zhou¹⁶ used porous PMMA samples to study the damage mechanism of coal rock cracks.¹⁷ They concluded that jet pressure and perforation length are the main parameters affecting fracture distribution, and it is easier for SC-CO₂ stress waves than other types of waves to form a complex fracture network. Yan¹⁸ constructed a fluid–solid coupling model to analyze the fracturing process of the SC-CO₂ phase change and realized the relationships between the SC-CO₂ injection volume and the length and

Received: June 1, 2021
Published: September 14, 2021

ACS Omega 2021, 6, 24462−24472
width of fracture expansion. Zhang\textsuperscript{17} claimed that increases in the stress wave intensity, the number of vent holes, and the reaming area accelerated the fracturing speed of liquid (L)-CO\textsubscript{2}. However, with small samples, the damage to the sample is caused only by the explosion stress wave, and there is not enough time for the splitting effect of high-pressure CO\textsubscript{2}. Wang\textsuperscript{18} found that different CO\textsubscript{2} gas pressures led to different damage patterns and degrees of crack development during the explosion process. The mechanism of crack propagation in coal rock caused by a CO\textsubscript{2} gas explosion has become a hot issue for researchers.

Li\textsuperscript{19} and Chen\textsuperscript{20} claimed that the process of a gas explosion breaking through rock is dynamic, and it is a major influence on the expansion of cracks. The action time of CO\textsubscript{2} explosive gas is as long as 10 ms ~ 30 ms, which can cause the high-pressure gas to fully penetrate the crack tip.\textsuperscript{21} Under the action of a CO\textsubscript{2} gas explosion, crack tips develop continuously. However, existing studies have not given a reasonable explanation of the effects of CO\textsubscript{2} gas explosions. Xie\textsuperscript{21} used field tests to prove that CO\textsubscript{2} gas explosions could promote the development of preexisting fractures in rock masses. Li\textsuperscript{22} proved that under the action of a CO\textsubscript{2} gas explosion, when the stress intensity factor of the crack tip was more than the fracture toughness of the crack, the crack further extended and propagated. Zhou\textsuperscript{8} analyzed the critical intrusion pressure required for fluid to overcome capillary forces to enter rock pores; he concluded that SC-CO\textsubscript{2} fracturing does not produce fluid lag and can easily form a more complex fracture network. The CO\textsubscript{2} gas explosion process can be divided into two processes, dynamic loading and static loading.\textsuperscript{23,25} Due to the synergistic effect of a gas explosion and stress waves, the crack expansion speed and stress intensity factor fluctuate during the explosion.\textsuperscript{26} After the main crack is formed by a CO\textsubscript{2} explosion, a large amount of low-temperature, high-pressure CO\textsubscript{2} gas remains inside the rock mass, acts on the crack tip generated by the instantaneous explosion load, and makes the crack tip extend. A field test\textsuperscript{21} proved that after the formation of the main crack, a CO\textsubscript{2} gas explosion continues to have an effect until the stress and strain stop changing; i.e., gas from an explosion has a certain influence on crack propagation in a coal rock mass. Because a CO\textsubscript{2} gas explosion occurs instantaneously, the laboratory experimental process is often limited by sample size, experimental conditions, and monitoring methods. The splitting effect of the explosion gas on the crack tip after the formation of the main crack has not been studied sufficiently. The use of precracked samples to simulate the mechanical properties of crack tips has become a technical means to study the effects of explosive gas on a crack tip. Haeri\textsuperscript{27} comprehensively and profoundly summarized the influence of nonpersistent joints on the stability of rock structure. Through the analysis and sorting of the research on the structural instability of rock materials with prefabricated joints, it is concluded that the joint spacing and joint persistence have an important impact on the failure mechanism of rock bridge, which provides a strong guidance for the test means and development direction of nonpersistent joint structural instability; it can be seen that it is feasible to use prefabricated cracks to study the structural instability of rock materials.

Thus, at present, researchers often ignore the effects of continuous vibrations on residual high-pressure CO\textsubscript{2} gas in cracks. Our innovative research proposes and completes numerical and experimental analyses of the propagation of prefabricated cracks in CO\textsubscript{2} gas explosion briquettes and uses simulations to study the repropagation mechanism of explosive cracks under the splitting action of CO\textsubscript{2} gas. We research the opening rates of precrack tips and the spatiotemporal evolution characteristics of energy fields in coal briquettes to provide engineering references for CO\textsubscript{2} explosion technology.

2. THE MECHANISM OF PREFABRICATED CRACK PROPAGATION BY A CO\textsubscript{2} GAS EXPLOSION

2.1. CO\textsubscript{2} Gas Pressure Attenuation at the Crack Tip. Gas pressure at a crack tip has an important influence on crack propagation.\textsuperscript{28} The following hypotheses are proposed to analyze the mechanism of crack propagation: (1) CO\textsubscript{2} gas in the crack satisfies the ideal gas state equation. (2) A ground stress field is stable during the CO\textsubscript{2} explosion. (3) Inelastic deformation occurs only in the infinitesimal area of a crack tip. (4) CO\textsubscript{2} gas flows isothermally at the moment of crack tip propagation without heat exchange with the crack walls. (5) A burst crack is a wedge-shaped crack with constant width. (6) The tensile crack at a crack tip is generated only under the action of tensile stress. Assuming that the radius of the gas burst tube is R and the length of the precrack is L, the precrack propagation model is shown in Figure 1.

\begin{align}
\frac{1}{r} \frac{\partial}{\partial r} \left( r \rho \delta \right) + \frac{\partial}{\partial y} \left( \rho \delta v_y \right) &= -2 \rho v_s \\
\rho \delta \left( \frac{1}{\rho} \frac{\partial p}{\partial y} + \lambda \right) &= -\frac{\partial}{\partial t} \left( \rho \delta v_z \right) - \frac{\partial}{\partial y} \left( \rho \delta v_y \right)
\end{align}

where \( \rho \) and \( v_s \) are the gas density (kg/m\textsuperscript{3}) and lateral velocity of the flow section (m/s), respectively, and \( p \) is the gas pressure (MPa). \( \delta \) is the crack opening displacement (m). \( \lambda \) is the friction coefficient, \( \lambda = \left( \frac{12\mu}{\rho \delta v_s} + 0.1 \right)^{0.5} \left( \frac{x}{\delta} \right) \approx \frac{12\mu}{\rho \delta v_s} \), where \( x \) is the sidewall loss rate, \( v_s = \frac{P - \phi}{\sqrt{\mu} \rho} \), \( K \) and \( \phi \) are the permeability and porosity of the coal rock mass, respectively, \( \mu \) is the viscosity coefficient of CO\textsubscript{2} gas, \( P \) and \( \rho \) are the gas and
initial gas pressure during the process of fracture, respectively, and \( t_0 \) is the start time of pore flow.

Since \( R_0 = \rho d \), we can ignore the inertial force. If the permeability of the coal rock mass is not considered, then the mass flow rate of \( CO_2 \) gas per unit volume is \( q = \rho d \nu \), and the \( CO_2 \) flow equation can be derived as shown in eqs 2 and 3.

\[
\frac{\partial q}{\partial y} = -\frac{1}{r} \frac{\partial}{\partial y} (r \rho \delta)
\]

(2)

\[
\frac{\partial p}{\partial y} = -\frac{12 \mu q}{\rho \delta^3}
\]

(3)

By introducing the initial boundary conditions \( q = q_{in} \), \( p = P_0 \), and \( r = r_c \), and integrating eq 2, we obtain eq 4.

\[
q = \frac{r^2}{2} \rho d_0 - \frac{1}{r} \int_{r_c}^{r} r \frac{\partial (\rho \delta)}{\partial y} \, dy
\]

(4)

If the change in \( \rho \) with time is very small, then the second term of eq 4 can be ignored, and eq 4 becomes \( q = \frac{r^2}{2} \rho d_0 \). By substituting \( q = \frac{r^2}{2} \rho d_0 \) into eq 3, we obtain eq 5:

\[
\frac{\partial p}{\partial y} = -\frac{12 \mu r_c q_0}{\rho \delta^3}
\]

(5)

Integrating eq 5 on both sides gives

\[
p = P_0 - \frac{12 \mu r_c q_0}{\rho \delta^3} \ln \frac{r}{r_c}
\]

(6)

If \( \rho \) is a constant and the \( CO_2 \) gas satisfies the ideal gas state equation, then substituting \( P_0 = \frac{\rho M}{RT} \) into eq 6 yields

\[
p = P_0 - \frac{12 \mu r_c q_0 RT}{P_0 \rho \delta^3} \ln \frac{r}{r_c}
\]

(7)

Now, we can calculate and explain the mass flow parameter \( q_{in} \) of \( CO_2 \) gas per unit volume in eq 7. At present, according to engineering practices in China, the explosion pressure is generally higher than 200 MPa. For example, the rated explosion pressure of the ZDZL100 \( CO_2 \) cracker can reach 270 MPa. We assume that the ambient gas pressure in the explosion environment is 1 standard atmospheric pressure and the \( CO_2 \) gas adiabatic coefficient \( k \) is 1.29. The atmospheric pressure around the vent hole of the cracker is \( P_0 \), the burst pressure is \( P_0 = \frac{\rho d}{r} < \left( \frac{2}{k+1} \right)^{k+1} \), and the \( CO_2 \) explosion gas flow is a sonic flow. The mass flow rate in the explosion process29 is shown in eq 8.

\[
q = -\frac{d q_{in}}{d t} = \frac{2}{y+1} \left( \frac{C_4 \rho M}{RT} \right)^{\frac{y+1}{y-1}}
\]

(8)

where \( q \) is the mass flow rate of \( CO_2 \) gas per unit volume (kg/s), \( q_{in} \) is the gas mass (kg), \( C_4 \) is the gas leakage coefficient, and the circle is \( C_4 = 1 \). \( y \) is the adiabatic coefficient of \( CO_2 \) gas (1.29), and \( M \) is the molar mass of \( CO_2 \) gas (44 kg/mol). \( S \) is the area of the vent (m²), and \( R \) is the molar gas constant (8.314 J·mol⁻¹·K⁻¹). \( T \) is the ambient temperature of the explosion process (K), and \( P \) is the \( CO_2 \) gas pressure in the vent (MPa).

From eq 8, the mass flow parameter at the crack tip during the \( CO_2 \) gas explosion depends on the area of the vent hole \( S \) and the pressure \( P \). The mass flow rate of \( CO_2 \) gas per unit volume differs according to the specifications of a cracker. During our experiment, the vent was a circle with a diameter of 2 mm, and the initial pressure was 2 MPa, so \( q_0 = 0.14 \) kg/s.

2.2. Crack Tip Opening Rate. According to the planar strain linear elasticity theory, the crack propagation in Figure 1 can be simplified to the solution of the biharmonic function, and the general solution for the amount of crack opening is30

\[
u_0 = \alpha \left[ -\frac{\nu \phi}{E} \left[ -B'(r) + \frac{1}{r} \int_a^{r} \left( B'' + 2\frac{\epsilon}{y} \right) dy \right] - A_1 \phi \right.
\]

\[
- \frac{\nu \phi}{E} \left[ -D'(r) + \frac{1}{r} \int_a^{r} \left( D'' + 2\frac{\epsilon}{y} \right) dy \right] - A_2 \phi
\]

\[
- \frac{\nu \phi}{E} \left[ D'(a) + 2G \right] + \cdots
\]

(9)

where \( \alpha \) is the included angle of the crack tip; \( B \) and \( D \) are functions of \( R \); and \( \epsilon \) and \( G \) are constants.

Due to the change in the stress–strain distribution at the crack tip, progressive matching cannot be carried out, and the crack tip area needs to be analyzed.31,32

The thickness of boundary layer at the crack tip is

\[
\rho = \frac{2(r - (L + R))}{\alpha}
\]

(10)

Then, the boundary condition in the boundary layer at the crack tip is

\[
\tau_{\theta=\pm 1} = -p(r) = -p(r - (L + R))
\]

\[
- \rho \alpha p [r - (L + R)] + \cdots, \quad \rho < 0
\]

\[
u_\theta=\pm 1 = 0, \quad \rho < 0
\]

By introducing eq 10 into eq 9, we obtain an asymptotic expansion for the amount of opening in the boundary layer at \( r = L + R \):

\[
\chi = -\alpha p \int_e^{L+R} p(y) dy + \alpha^2 \chi_0^2 + L
\]

\[
u_0 = \alpha \chi_0^2 + L
\]

where

\[
\frac{d \chi}{d \phi} = \frac{1}{E} \left[ \tau_{\phi=0} \frac{\rho d}{\rho d \phi} - \nu \tau_{\phi=0} \right],
\]

\[\int_a^b \frac{d \chi}{E \rho d \phi} = -\frac{1}{E} \frac{\rho d}{\rho d \phi} \left. \frac{\rho d^2}{\rho d \phi^2} \right|_a^b
\]

\[
\Omega = 0;
\]

The boundary conditions are
\[ \tau_{\theta 1} = 0 \]
\[ \tau_{\theta 0} = \frac{-p(L + R)}{L + R} \left[ \lim_{\rho \to 0} + \right] \left( \frac{1}{L + R} \left[ \rho \theta p + \int_{0}^{L + R} p(y) \right] \right) \]

The crack tip opening displacement under the action of an explosive gas is solved approximately, as shown in eq 11,
\[ u_p = \frac{\alpha}{2E} \left( p(r) + \frac{1}{r} \int_{r}^{R} \frac{1}{p} \left( p_0 + \int_{R}^{L + R} p_0 \right) \right) \]
\[ + \left( \int_{R}^{L + R} p_0 \right) \left( \frac{1}{2} \theta \right) \]

where \( \alpha \) is the angle of the crack tip, and \( p_0 \) and \( p(x) \) are the initial gas pressure and the crack tip pressure (MPa), respectively.

When only the quantity of vertical ground stress is considered, \( \sigma_{y y} = 0 \), the gas pressure distribution equation in eq 7 is used, and the opening rate of the precrack tip is obtained as shown in eq 12,
\[ \nu = \frac{\delta}{\Delta t} \]
\[ \frac{\partial u}{\partial t} + \frac{\partial (\nu u)}{\partial x} = 0 \]
\[ \int_{R}^{L + R} \left[ p_0 \right] \left( R + R \right) \left( \frac{1}{2} \theta \right) \]
\[ + \frac{2\pi}{\Delta t} \left( \int_{R}^{L + R} \left[ p_0 \right] \right) \left( \frac{1}{2} \theta \right) \]
\[ + \frac{2\pi}{\Delta t} \left( \int_{R}^{L + R} \left[ p_0 \right] \right) \left( \frac{1}{2} \theta \right) \]

where \( \sigma_{y y} \) is the quantity of ground stress (MPa), \( \alpha \) is the angle of the crack tip, \( \delta \) is the width of crack propagation, and \( \Delta t \) is the time interval from the initiation of the crack to the end of its propagation.

2.3. Crack Tip Growth Rate. According to the Irwin–Orowan energy balance theory, \( E_{k} \) the energy conservation equation of precrack tip propagation can be obtained:
\[ \Delta W = \Delta U_{e} + \Delta W_{s} + \Delta E_{k} \]  
\[ \delta = \frac{\partial u}{\partial t} + \frac{\partial (\nu u)}{\partial x} = 0 \]
\[ \int_{R}^{L + R} \left[ p_0 \right] \left( \frac{1}{2} \theta \right) \]
\[ + \frac{2\pi}{\Delta t} \left( \int_{R}^{L + R} \left[ p_0 \right] \right) \left( \frac{1}{2} \theta \right) \]
\[ + \frac{2\pi}{\Delta t} \left( \int_{R}^{L + R} \left[ p_0 \right] \right) \left( \frac{1}{2} \theta \right) \]

where \( \Delta W \) is the total work done by CO2 gas on the system; \( \Delta U_{e} \) is the elastic strain energy; and \( \Delta W_{s} \) is the separation work, i.e., the energy released by the crack; and the crack growth length is \( a \). \( \Delta E_{k} \) is the increase in kinetic energy.

The total work done by a CO2 gas explosion is
\[ \Delta W = \int_{0}^{a} \int_{y}^{y+\Delta y} pd\delta dr \]

If \( r \approx a \) and the material undergoes dynamic fracture under a high strain rate, then according to Nishioka, \( E_{k} \) the expressions for the crack tip displacement field in the compound mode and the crack tip velocity field are
\[ U_{x} = \frac{K_{1} B_{1}(v)}{\mu \Delta t} \left( \frac{2a}{\pi} \right) \theta \left( \frac{2\beta_{K}}{1 + \beta_{K}^{2}} - \beta_{1} \right) \]
\[ U_{y} = \frac{K_{1} B_{1}(v)}{\mu \Delta t} \left( \frac{2a}{\pi} \right) \cos \theta \left( 1 - \frac{2\beta_{1} \beta_{2}}{1 + \beta_{2}^{2}} \right) \]

where \( \mu \) is the modulus of elasticity, \( C_{p} = \sqrt{\beta(1 + \mu) / (1 - 2\mu)} \) is the longitudinal wave velocity (m/s), and \( C_{s} = \sqrt{\beta(1 - 2\mu) / (1 - \mu)} \) is the longitudinal wave velocity (m/s), \( B_{1}(v) = \sqrt{\beta(1 + \beta_{2}^{2}) / (1 + \beta_{2}^{2})} \), \( \beta_{1} = \sqrt{1 - \frac{\beta_{2}^{2}}{c_{n}^{2}}} \), and \( \beta_{2} = \sqrt{1 - \frac{\beta_{2}^{2}}{c_{n}^{2}}} \).

According to the method proposed by Rummel \( W_{s} \) to calculate the stress intensity of compound cracks, we use the pressure attenuation coefficient \( \sigma_{y y} = \frac{1}{2} \beta_{2} \). If only the influence \( \sigma_{y y} \) on the prefabricated crack is considered, then the stress intensity factor is shown in eq 16.
\[ K_{i} = C_{0} + \frac{P_{0}}{R_{0}} \left( 1 - \frac{2}{\pi} \sin \theta \right) \]

where \( C_{0} = 2\sigma_{y y} \left( \frac{R(b - 1)}{b^{2}} \right) + P_{0} \sqrt{R \left( 1.3 \beta_{2}^{2} - 7.8 \sin(0.5b - 1.7) \right)} \) and \( b = 1 + \frac{L}{R} \). Thus, the crack growth criterion is \( K_{i} \). By substituting eq 16 into the kinetic energy calculation equation, we obtain
\[ E_{k} = \frac{1}{2} \rho \left( \int_{\Omega} \left( U_{x}^{2} + U_{y}^{2} \right) dx \right) \]
\[ = \frac{a\rho B_{1}(v)}{\mu u^{2} \Delta t} \left( \frac{1}{2} \theta \right) \left( \frac{2\beta_{1}}{1 + \beta_{2}^{2}} - \beta_{1} \right) \]
\[ + \frac{1}{2} \left( 1 - \frac{2\beta_{1} \beta_{2}}{1 + \beta_{2}^{2}} \right) K_{i} \]

The kinetic energy increment is
\[ \Delta E_{k} = E_{k}(t + \Delta t) - E_{k}(t) \]

The elastic strain energy increment is
\[ \Delta U_{e} = \int_{0}^{a} \int_{y}^{y+\Delta y} \sigma_{y y} d\delta dr \]
\[ = \int_{0}^{a} \int_{y}^{y+\Delta y} \frac{K_{1} B_{1}(v)}{\sqrt{2a\pi}} \left( 1 + \frac{\beta_{1}^{2}}{1 + \beta_{2}^{2}} - \frac{4\beta_{1} \beta_{2}}{1 + \beta_{2}^{2}} \right) \]
\[ \left( \frac{1}{\sqrt{2\pi}} \frac{\cos \theta}{2} \right) d\delta dr \]

The energy release rate \( G \) can be expressed as
3. RESULTS AND ANALYSIS

3.1. Crack Growth Morphology and Crack Tip Displacement. Because the viscosity of CO2 gas is low, it is easier for gas from a CO2 explosion than gas mixtures from traditional gunpowder explosions to enter the natural pores in rock, thereby increasing the probability of opening and dislocating a preexisting fracture. Thus, the antireflection effect of a CO2 explosion is better than that of a dynamite explosion.18,38 The final crack propagation morphology of a CO2 gas explosion sample is shown in Figure 2.

Figure 2. Cross section of crack morphology.

Figure 2 shows the upper right quarter of the gas burst tube of a sample with three main cracks and a network of many somewhat well-developed secondary cracks near the main cracks. The cracks produced by a CO2 explosion differed from the single crack produced by a traditional gunpowder explosion because of the special physical and chemical properties, such as viscosity, of CO2. Many secondary cracks formed a weak structure, which made the cracks further interpenetrate, develop, and expand in the coal body.

For example, for sample A-III with an axial pressure of 1 MPa and CO2 gas pressure of 2 MPa, the upper part of the sample was used to analyze the tip propagation characteristics of the precrack. The sample explosion lasted 309 ms. The images collected using a VIC-Snap system were subjected to grayscale processing, the contrast and brightness of the images were adjusted to obtain the crack growth form, and a planar Cartesian coordinate system was established on the basis of the image centroid, as shown in Figure 3.

In the irregular planar area \((x,y) = \{[-1.64,2.53],[-21.3,30.0]\}\) (mm, mm) in Figure 3, the speckles fell off the sample surface under the action of the CO2 gas explosion. The images were digitized, and their typical characteristics were studied during the whole cycle. Haeri39 proposed that crack coalescence is always a combination of wing cracks and shear cracks. Obviously, this conclusion is verified in Figure 3. The prefabricated crack tip propagated under the splitting action of CO2 gas and formed a tensile crack with a relatively smooth crack surface and no crushed particles. After the beginning of the explosion, the sample did not reach its ultimate strength at 19 ms. The surface displacement of the sample changed uniformly at the tip of the precrack, and the maximum displacement was 0.00285 mm. At 292 ms, the prefabricated cracks began to fail locally. The moment that the crack tip reached the ultimate strength of the matrix was the critical moment for the calculation of the crack tip extension initiation time. The area \((x,y) \in \{[-0.25, -1.64], [-21.3, -21.5]\}\) (mm, mm) was the result of local material flaking off the observed surface under the action of CO2 gas. The initial crack tip propagation occurred in the second quadrant, and the maximum displacement was −0.2958 mm. The maximum positive x displacement was 0.1331 mm, and the initial crack length was only 0.45 mm. The sample began to show a ladder-like distribution around the prefabricated crack tip centered at x. The negative displacement was larger than the positive displacement. From 295 to 309 ms, the negative x displacement ranged from −0.3804 to −0.8322 mm, and the positive x displacement ranged from 0.1531 to 0.3669 mm. The negative displacement increment of x was always larger than the positive displacement, mainly due to initial crack growth in the second quadrant. After the initial crack formed, it deflected and grew in the direction toward the local damage area. The displacement first increased and then decreased, and the length of the main crack extended from 11.82 to 34.21 mm. The initiation and propagation processes of the crack tip in this test were the same as those for the first type of propagation mode initiated from crack tips in the study by Sarfarazi and Haeri;40 this explained the similarity of the propagation relationships in this study and that of Sarfarazi et al.

At 309 ms, crack propagation stopped. In Figure 3d, secondary cracks around the gas explosion tube were observed on the left side of the gas explosion tube. After the formation and full development of the main crack, CO2 gas was loaded in resonance with the weak structure and gradually penetrated the main crack, and the crack tip underwent an explosion. This oscillation led to the formation of a network of secondary cracks. In addition, due to the presence of the gas explosion tube, secondary cracks formed in the material around the circumference of the gas explosion hole due to local shear stress.

3.2. Prefabricated Crack Tip Opening Rates and Increments. We assumed that the sample material was isotropic and only elastic deformation occurred during the crack propagation process, and we approximated the cracking strain by the first principal strain component.41,42 We considered a microcrack damage area with infinitesimal width \(d_0\) and length of \(l_0\) at the prefabricated crack tip. Since \(d_0 < l_0\), we made the approximation that the microcrack damage area at the crack tip was uniformly distributed on \(l_0\), and thus, the cracking strain \(\epsilon_1 = dw/dx\), as shown in Figure 4.
The equivalent crack opening displacement $\bar{d}$ can be calculated using eq 23:

$$
\bar{d} = \int_{-\frac{d_0}{2}}^{\frac{d_0}{2}} \varepsilon_1 dx = \frac{d_0 \varepsilon_1}{2}\cos \theta
$$

where $\varepsilon_1$ is the total strain, namely, the elastic strain. $\theta$ is the angle between the crack tip and the normal direction, and the initial time is 0. $\varepsilon_1$ is the first principal strain, and it is in the direction normal to the direction of fracture.

The crack tip opening rate $v$ is given in eq 24:

$$
v = \frac{d_0 \varepsilon_1 \cos \theta}{\Delta t}
$$

We took the digital speckle image at the time that CO$_2$ gas pressure was not applied as the reference system. Calculation points A ($-7.5, 21.5$) and B ($7.5, 21.5$) were selected as displacement tensor calculation points at symmetrical positions on both sides of the precrack tip. According to eq 22, the precrack tip opening rate curve is the ratio of opening...
displacement and time. $V_c$ and $dV_c$ were calculated at different times during the experiment, as shown in Figure 5.

![Figure 5. Prefabricated crack opening rate and increment curve.](image)

From Figure 5, the crack opening rate at 309 ms, calculated using eq 10, was 1.38 m/s, and the theoretical error, calculated using eq 22, was 7%, which verified the utility of the calculation and equations. The opening rate of the precrack tip included three stages. Stage I: In the 0–289 ms range, due to the resonance of CO$_2$ gas, the opening rate fluctuated in the $[-0.00677, 0.0043]$ interval and then increased slowly. Point M(289, 0.0043) was the inflection point of the expansion rate. The rate at 289 ms increased by 18.78% compared to the rate at 288 ms, and then, the rate increment per unit time ($dV_c$) gradually increased. Stage II: In the 290 ms ~ 295 ms range, $V_c$ increased significantly, and the crack tip opening rate increased the fastest. At 291 ms, the $dV_c$ value was maximum, and the maximum incremental value was 0.1865 m/s, which was approximately consistent with the observations of initial crack growth and displacement in Figure 5b. We used the least square method to fit the 290 ms ~ 294 ms curve; the crack opening rate function at stage II was $y_{II} = 0.1166x - 0.0653$ and $R^2 = 0.9683$, and the slope was $k_{II} = 0.1166$. Stage III: In the 295 ms ~ 309 ms range, $V_c$ continued to increase, but the increase in the crack tip opening rate was significantly less than that at stage II, and $dV_{III}$ gradually decreased. All increment $dV_{III}$ values at stage III were reduced by 0.4658 m/s compared with all increments at stage II. In the 295 ms ~ 309 ms range, the crack opening rate functions of stage III obtained by fitting the curve was $y = 0.0637x + 0.5328$, $R^2 = 0.9971$, and slope $k_{III} = 0.0637$.

3.3. Crack Tip Growth Rate. The explosion occurred quickly, and the displacement field no longer had the characteristics of the reaction crack propagation mechanism. During the explosion, the crack tip had a high strain rate and large deformation area, and the speed was often used to describe the crack propagation mechanism. In this experiment, a high-definition image of the entire explosion process was collected with a VIC-Snap system at 1 image per 1 ms and used to obtain the crack tip growth coordinates; the crack tip growth rate was calculated using eq 25.

$$\frac{\nu \Delta l}{\Delta t} = \frac{1}{\Delta t} \int_{t_1}^{t_{t+1}} \sqrt{(x_{t+1} - xt)^2 + (y_{t+1} - yt)^2} dt$$

(25)

The rate evolution curve of the sample expansion process is shown in Figure 6.

![Figure 6. Evolution curve of the gas explosion crack growth rate.](image)

According to Figure 6, the maximum crack growth rates obtained by theoretical calculations and experiments were 5.73 and 5.81 m/s, respectively, and the error was relatively small. In the experiment, at 0–290 ms, the energy storage stage, CO$_2$ gas continuously eroded the sample materials around the gas burst tube. The environment around the gas burst tube had not yet reached a steady state, and the average expansion crack growth rate was only $8.144 \times 10^{-4}$ m/s. After 291 ms, the crack tip growth rate gradually increased, reaching a maximum at 295 ms. At 296–309 ms, the crack growth rate gradually decreased, and the maximum growth rate was 5.35 m/s. As a result, from the beginning of the gas explosion loading, the growth rate of the prefabricated crack tip underwent a dynamic growth process that first increased quickly and then increased slowly. After 309 ms, the crack growth rate was smaller than the tip growth rate at the time of crack initiation, the time when the crack stopped growing. The relationships for the opening rate of the precrack and the tip growth rate are consistent in the three stages, which verified the growth characteristics of the precrack tip.

3.4. Law of Energy Evolution. We assumed that the material at the crack tip remained elastic and calculated the elastic strain energy density according to eq 26:

$$h = \frac{E}{2}(\varepsilon_1^2 + \varepsilon_2^2 - 2\mu\varepsilon_1\varepsilon_2)$$

(26)

where $\varepsilon_1$ and $\varepsilon_2$ are the first and second principal strains, respectively.

By calculating the full strain field from data obtained by VIC-3D, we obtained the first and second principal strain data during the CO$_2$ gas explosion. Then, we used a MATLAB program to invert the energy field during the crack propagation process according to eq 8. The strain energy density cloud diagram of the prefabricated crack propagation process of the CO$_2$ gas explosion was obtained through evolution, as shown in Figure 7.

From Figure 7, the evolution process of CO$_2$ explosion strain energy was consistent with the crack evolution
relationship in Section 4.1 and was mainly manifested in three stages. 

Stage I: In the 0∼289 ms range, CO2 gas had not yet filled the tip of the precrack, and the explosive gas continuously leaked from its tip. The increasing energy in the form of simple harmonic waves changed uniformly over a small range, and the energy had not yet accumulated and was relatively small. The maximum energy density in Figure 7a was only 0.0039 kJ/m³.

Stage II: In the 290 ms ∼ 293 ms range, the tip of the prefabricated crack was filled with CO2 gas, and the growth rate of the crack tip was relatively stable. Energy began to accumulate rapidly at the tip of the prefabricated crack. The maximum energy density in Figure 7b was 0.0878 kJ/m³, more than three orders of magnitude greater than the average energy density of stage I and the fastest stage in the evolution of strain energy. Initially, energy accumulation concentrated at the crack tip and propagated in the direction of relatively low material strength and greater local damage.

Stage III: In the 295 ms ∼ 309 ms range, enough energy accumulated at the crack tip to cause the material to fracture. Microcracks were generated locally at the crack tip, and energy release began. Figure 7c shows that due to the occurrence of local microcracks, the surface speckles began to fall off, which interfered with the measurement of energy concentration. At 295 ms, the strain energy density reached the maximum value of 0.7741 kJ/m³, after which the energy was reduced to a lower level until the end of the experiment.

In addition, from Figure 7c to d, due to the formation of erosion pits and the expansion of the crack tip, the material around the gas burst tube was locally damaged and the gas explosion effect of CO2 caused a circular ring of secondary cracks around the gas burst tube.

We chose five points A (−7,8), B (−7,16), C (−7,24), D (−7,32), and E (−7,40) along the edge of the precrack tip and calculated the strain energy density curve $h_A ∼ h_E$, as shown in Figure 8.

According to Figure 8, crack energy evolution at the different positions was as follows. (1) Closer to the tip of the precrack, the strain energy first increased and then decreased over a short period of time, and the material was more prone to damage. The $h_A$ curve was only 9 mm from the tip of the precrack. At 293 ms, the energy of the crack tip reached 0.8493 kJ/m³ and began to release. At 303 ms, the tip energy of the $h_E$ curve was 1.5447 kJ/m³, which was approximately 1.8 times the maximum energy of the $h_A$ curve, and the apparent action time relatively increases by 12 ms. (2) The crack growth process changed at a nonuniform speed, and the energy change was nonlinear. The moments at which $h_A ∼ h_E$ reached the maximum strain energy were 293, 295, 296, 298, and 303 ms. If the initial moment of energy release is regarded as a microcrack in a unit area of the material, then the progress of crack propagation is indicated at the same distance in the A ∼ E points. Obviously, the crack propagation process changed at a nonuniform speed after 288 ms.

In summary, the energy evolution indirectly proved the presence of three stages of CO2 gas explosion, i.e., precrack initiation, crack arrest time, and propagation. Stage I: In the 0∼289 ms range, there was the crack tip energy storage stage. Stage II: In the 290 ms ∼ 295 ms range, there was the rapid crack propagation stage. Stage III: In the 296∼309 ms range, there was the slow crack growth stage.

4. DISCUSSION AND CONCLUSIONS

The study of the crack repropagation mechanism of CO2 gas splitting in fractured coal and rock masses is of great importance.
significance to the study of CO2 deep-hole presplitting blasting antireflection technology. According to previous laboratory test research that was limited by the sample size, a CO2 gas explosion instantaneously reaches a steady state, which ignores the continuous oscillations of residual high-pressure CO2 gas in the crack that are observed in the field. In contrast, this innovative study proposed and completed numerical experimental analyses of CO2 gas explosions and prefabrication crack propagation in briquettes and used simulations to study the repropagation mechanism of explosion cracks under the action of CO2 gas splitting. Through fluid motion equations, the analytical solutions of gas pressure attenuation at different positions were derived. Based on linear elasticity and energy balance theory, the opening and propagation rates of the crack tip were calculated and verified by experimental results. For the first time, the energy field of the whole process of CO2 blasting was inverted, and the starting and stopping times and coordinates were obtained through the energy release theory. Through the analysis of energy accumulation and release processes, the dominant influence of explosive gas in the CO2 gas explosion briquette test was indirectly verified. The objective development of preformed crack propagation in briquettes under CO2 gas splitting was comprehensively discussed, including crack morphological characteristics, displacement changes, opening and propagation rates, and energy field evolution processes. In this study, the crack opening and propagation rate curves proved that the numerical results were in good agreement with the experimental results, which can improve understanding of the mechanism of CO2 gas at a crack tip. The main results are as follows:

1. The propagation of a prefabricated crack tip was mainly due to tensile failure caused by the splitting effect of CO2 gas that accumulated at the crack tip.

2. There were three stages in the growth process of prefabricated cracks under conditions of a CO2 gas explosion. Stage I: In the 0~290 ms range, the crack tip energy storage stage, the maximum opening rate increase was 0.0043 m/s. Stage II: In the 291~295 ms range, the rapid crack growth stage, the maximum opening rate increment and growth rates were 0.1865 and 5.35 m/s, respectively. Stage III: In the 296~309 ms range, the slow crack growth stage, the maximum opening rate increment and the expansion rates were 0.0969 and 5.81 m/s, respectively. The crack arrest coordinates were (4.57 mm, 35.28 mm).

3. The crack initiation and arrest times were 291 and 309 ms, respectively, based on the energy release process. The strain energy near the crack tip first increased and then decreased, the energy changed over a brief period of time, the rate of crack growth was nonuniform, and the energy changed nonlinearly.

Parameters such as the crack growth and crack opening rates obtained from this experiment can provide experimental laboratory support for field tests. However, due to the limitations of these experimental conditions, subsequent experiments should be carried out in a relatively closed-box environment. In addition, future experiments should model the coal seam and its adsorption and mechanical properties as closely as possible. Researchers should consider related conditions such as gas concentration to provide a better theoretical guidance for CO2 gas explosion antireflection technology.

5. EXPERIMENTAL SECTION

In most laboratory experiments and studies, due to the limitation of the sample size after the formation of the main crack by a CO2 explosion, the damage to the sample is assumed to be mainly caused by an explosion stress wave because there is not enough time for the splitting effect of high-pressure CO2. It is difficult to obtain samples with main cracks in the experiments. For this reason, bilateral cracked samples are prefabricated, and the dynamic response mechanism of precrack tip propagation under the action of a CO2 gas explosion at the crack tip is explored.

5.1. Experimental System. To carry out the CO2 gas explosion experiment, we independently designed and developed a CO2 explosion test platform, which was mainly composed of a loading system, an explosion system, and an observation system. The loading system was a DNS-200 electronic universal testing machine that we used to measure the basic physical and mechanical parameters of the samples and applied constant axial pressure to each sample before the start of an experiment. The CO2 gas explosion experiment system was composed of a CO2 gas cylinder, a pressure reducing valve, two high-pressure solenoid valves, two pressure gauges, and an explosion-proof charging device, which was convenient for releasing constant air pressure at the moment of the explosion experiment to blast the coal rock mass. We used a VIC-3D system to observe the crack tip strain fields and displacement fields of the samples, and we acquired information on the crack tip strain field through data post-processing. The experimental system is shown in Figure 9.

![Experimental system](https://doi.org/10.1021/acsomega.1c02850)

**Figure 9.** Experimental system.

5.2. Samples. There are many mesoscopic cracks in a slit specimen at the crack tip, which makes it difficult to collect speckle images of the crack tip and impossible to accurately measure changes in the strain and displacement of the precrack tip. Drilled core samples are difficult to process, and sample homogeneity cannot be guaranteed. The mechanical properties of coal powder, cement, and gypsum mixture samples are similar to those of the coal rock mass, and the cost is low. Before carrying out an experiment, we found that coal powder, cement, gypsum powder, and water with a mass ratio of...
1:2:1:0.8 worked well with the gas explosion pipe, and CO₂ gas did not easily leak and form spouts, so we used this ratio to make samples. First, the materials were mixed evenly according to the ratio and put into a 70 mm × 70 mm × 140 mm cuboid mold. The mold was inserted into a gas explosion tube, and a precracked specimen with a crack size of 10 mm × 0.2 mm was placed in the center of the mold. The mold was shaken, and the contents were demolded after 30 min. Second, the precracked piece was removed, and the sample was allowed to set for 28 days in a constant temperature and humidity oven at 19~24 degrees Celsius and humidity of 20% ~ 30%. Finally, the surface of the sample was polished and trimmed. An example is shown in Figure 10.

Before the start of an experiment, a triaxial compressive strength experiment was performed to obtain the basic physical and mechanical parameters of the sample. Ultrasonic experiments were used to calculate the transverse and longitudinal wave speeds of the samples. The physical parameters are shown in Table 1.

5.3. Experimentation. Before we started an experiment, we used petroleum jelly to coat the upper and lower ends of the sample to eliminate the influence of end effects on the experiment. We used a DNS200 Press and set the flow parameters to complete the explosion experiment. The loading method was force control, and the loading speed was 0.05 kN/s, due to the low strength of the samples. The loading target, 5 kN, was applied to a sample with a constant pressure of 1 MPa and maintained for 5 min. The main steps of the experiment were as follows:

(a) After debugging the experimental system, observe the pressure indicator and adjust the pressure reducing valve to reach a constant pressure of 2 MPa.
(b) Turn on the high-pressure solenoid valve switch to quickly release CO₂ gas into the samples.
(c) Use a VIC-Snap system to collect images at the beginning of the explosion. The collection time interval was set as 1 ms to obtain information on the strain and displacement fields at the prefabricated crack tip in real time during the explosion.
(d) Repeat the above steps and record and process data.

During the sample preparation process, the gas burst tube was connected to the material. The vent hole of the gas explosion tube was located at the end of the tube with diameters of 10 and 2 mm, respectively. The upper and lower constant pressures limit the explosion of the sample. The explosion gas pressure is relatively small, and the explosion process is relatively stable. Due to the use of PMMA protective equipment, it was safer not to have a larger explosion.

Table 1. Specimen Parameters

| E/GPa  | G/GPa  | σ/MPa | ρ/(kg·m⁻³) | μ | C/MPa | φ/(°) | C₀/(m/s) | C₀’/(m/s) |
|-------|-------|-------|------------|---|-------|-------|---------|---------|
| 2.50  | 1.008 | 4.59  | 1.25 × 10³ | 0.24 | 1.21  | 24.2  | 1088    | 1860    |

Notes
The authors declare no competing financial interest.

ACKNOWLEDGMENTS
This research was financially supported by the following funds: The National Natural Science Foundation of China (51874234). The authors are also grateful to the anonymous reviewers for their constructive comments.

REFERENCES
(1) Yuan, L. Strategic thinking of simultaneous exploitation of coal and gas in deep mining. J. Meitan Xuebao. 2016, 41, 1–6.
(2) Zhong, J.; Ge, Z.; Lu, Y.; Zhou, Z.; Zheng, J. Prediction of fracture initiation pressure in multiple failure hydraulic fracturing modes: Three-dimensional stress model considering borehole deformation. J. Pet. Sci. Eng. 2021, 199, No. 108264.
(3) Liming, Z.; Manping, Y. Simulation on the dynamic variation of downhole gas pressure during deflagration fracturing in screen completed well. Arab. J. Geosci. 2021, 14, 240.
(4) Pan, Y.; Zheng, M.; Xing, Z. Experimental Study on The Effect of Charge Structure of Blasting on Damage to Dirt Band in Thin Coal Seam. IOP Conf. Ser.: Earth Environ. Sci. 2019, 300, No. 022138.
(5) Gandossi, L. State of the art report on waterless stimulation techniques for shale formations: The Netherlands: Publications Office of the European Union; 2016.
(6) Perera, M. S. A. A comprehensive overview of CO₂ flow behaviour in deep coal seams. Energies 2018, 11, 906.
(7) Middleton, R. S.; Carey, J. W.; Currier, R. P.; Hyman, J. D.; Kang, Q.; Karra, S.; Jiménez-Martínez, J.; Porter, M. L.; Viswanathan,
H. S. Shale gas and non-aqueous fracturing fluids: Opportunities and challenges for supercritical CO₂. *Appl. Energy*. **2015**, *147*, 500–509.

(8) Zhou, D.; Zhang, G. A review of mechanisms of induced fractures in SC-CO₂ fracturing. *Pet. Sci. Bull*. **2020**, *S*, 239–253.

(9) Kutter, H. K.; Fairhurst, C. On the fracture process in blasting. *Int. J. Rock Mech. Min. Sci.* **1971**, *8*, 181–202.

(10) Chen, E. P. Transient stress analysis of high energy gas fracture experiments. *Theor. Appl. Fract. Mech.* **1984**, *2*, 217–231.

(11) McHugh, S. Crack extension caused by internal gas pressure compared with extension caused by tensile stress. *Int. J. Fract.* **1983**, *21*, 163–176.

(12) Yan, H.; Zhang, J.; Zhou, N.; Li, M. Staged numerical simulations of supercritical CO₂ fracturing of coal seams based on the extended finite element method. *J. Nat. Gas Sci. Eng.* **2019**, *65*, 275–283.

(13) Sun, K.; Xin, L.; Wu, D.; Wang, J. Simulation of fracture law of supercritical CO₂ explosion under initial stress condition. *J. Vib. Shock*. **2018**, *37*, 232–236.

(14) Sun, K. M.; Xin, L. W.; Wu, D. Experimental study on fracture mechanism of coal caused by supercritical CO₂ explosion. *Baozhu Yu Chongi*. **2018**, *38*, 302–308.

(15) Cai, C.; Kang, Y.; Wang, X.; Hu, Y.; Chen, H.; Yuan, X.; Cai, Y. Mechanism of supercritical carbon dioxide (SC-CO₂) hydro-jet fracturing. *J. CO₂ Util.* **2018**, *26*, 575–587.

(16) Zhou, D.; Zhang, G.; Zhao, P.; Wang, Y.; Xu, S. Effects of post-instability induced by supercritical CO₂ phase change on fracture dynamic propagation. *J. Pet. Sci. Eng.* **2018**, *162*, 358–366.

(17) Zhang, Y.; Deng, J.; Deng, H.; Ke, B. Peridynamics simulation of rock fracturing under liquid carbon dioxide blasting. *Int. J. Damage Mech.* **2019**, *28*, 1038–1052.

(18) Wang, L.; Yao, B.; Xie, H.; Winterfeld, P. H.; Kneafsey, T. J.; Yin, X.; Wu, Y. S. CO₂ injection-induced fracturing in naturally fractured shale rocks. *Energy*. **2017**, *139*, 1094–1110.

(19) Li, N.; Chen, L. J.; Zhang, P. Dynamic analysis for fracturing progress by detonation gas. *Yantu Gongcheng Xuebao*. **2006**, *28*, 460–463.

(20) Chen, L. J.; Li, N.; Wang, J. Q. Approximate analysis of fracture propagation driven by detonation gas in well oil. *Yanshi Luxue Yu Gongcheng Xuebao*. **2006**, *25*, 2369–2372.

(21) Xie, X. F.; Li, X. B.; Li, Q. Y.; Ma, H. P.; Liu, X. X. Liquid CO₂ phase-transforming rock fracturing technology in pike-while excavation. *Zhongnan Daxue Xuebao, Ziran Kexueban*. **2018**, *49*, 2031–2038.

(22) Lai, X. P.; Cui, F.; Cao, J. T.; Shan, P. F. Extra-thick coal blasting mechanism and numerical simulation of partial failure. *J. China Coal Soc.* **2014**, *39*, 1642–1649.

(23) Donzé, F. V.; Bouchez, J.; Magnier, S. A. Modeling fractures in rock blasting. *Int. J. Rock Mech. Min. Sci.* **1997**, *34*, 1153–1163.

(24) Nilson, R. H.; Proffer, W. J.; Duff, R. E. Modelling of gas-driven fractures induced by propellant combustion within a borehole. *Int. J. Rock Mech. Min. Sci.* **1983**, *20*, 1–22.

(25) Rabczuk, T.; Eibl, J. Modelling dynamic failure of concrete with meshfree methods. *Int. J. Impact Eng.* **2006**, *32*, 1878–1897.

(26) Wang, Y. Analysis of dynamic characteristics of through-wall cracks between 2 bores in the directed fracture controlled blasting. *Fatigue Fract. Eng. Mater. Struct.* **2018**, *41*, 273–286.

(27) Shemirani, A. B.; Haeri, H.; Sarfarazi, V.; Hedayat, A. A review paper about experimental investigations on failure behaviour of non-persistent joint. *Geomech. Eng.* **2017**, *13*, 535–570.

(28) Swenson, D. V.; Taylor, L. M. *Analysis of gas fracture experiments including dynamic crack formation*; Sandia National Labs: Albuquerque, NM (USA), 1982.

(29) Zhang, Y. Y. *Fluid mechanics 2nd edition*; Higher Education Press: Beijing, 2018, 398–429.

(30) Paine, A. S.; Please, C. P. Asymptotic analysis of a star crack with a central hole. *Int. J. Eng. Sci.* **1993**, *31*, 893–898.

(31) Haeri, H.; Shahrarai, K.; Marji, M. F.; Vand, P. M. *Simulating the bluntness of TBM Disc cutters in rocks using displacement discontinuity method*. 13th International Conference on Fracture (ICF13), 2013.

(32) Haeri, H. Experimental crack analyses of concrete-like CSCBD specimens using a higher order DDM. *Comput. Concr.* **2015**, *16*, 881–896.

(33) Orekhov, B. G.; Zertsalov, M. *Fracture Mechanics of Engineering Structures and Rocks*; AA Balkema: 2014, 1–40.

(34) Nishioka, T.; Aihara, S. Path-independent integrals, energy release rates, and general solutions of near-tip fields in mixed-mode dynamic fracture mechanics. *Eng. Fract. Mech.* **1983**, *18*, 1–22.

(35) Rosakis, A. J. Analysis of the optical method of caustics for dynamic crack propagation. *Eng. Fract. Mech.* **1980**, *13*, 331–347.

(36) Rummel, F. Fracture mechanics approach to hydraulic fracturing stress measurements. *Eng. Fract. Mech.* **1987**, *18*, 217–240.

(37) Guo, D. M.; Yan, P. Y.; Yang, R. S.; Yuan, B. S.; Zhou, B. W. Dynamic caustics test on the inclined cracks in roadway surrounding rock subjected to static-dynamic load. *J. Min. Saf. Eng.* **2016**, *33*, 668–675.

(38) Zhou, J.; Hu, N.; Xian, X.; Zhou, L.; Tang, J.; Kang, Y.; Wang, H. Supercritical CO₂ fracturing for enhanced shale gas recovery and CO₂ sequestration: Results, status and future challenges. *Adv. Geo-Energy Res.* **2019**, *3*, 207–224.

(39) Sarfarazi, V.; Haeri, H. Effect of number and configuration of bridges on shear properties of sliding surface. *J. Min. Sci.* **2016**, *52*, 245–257.

(40) Sarfarazi, V.; Haeri, H.; Fatehi, M. Fracture mechanism of Brazilian discs with multiple parallel notches using PFC2D. *Period Polyt. Civil Eng.* **2017**, *61*, 653–663.

(41) Lin, Y.; Yao, J.; Liu, Y.; Liu, Y.; Qiao, J.; Ding, Y. Preliminary numerical simulation of rock perforation cracking. *Baozhu Yu Chongi*. **2019**, *39*, 156–165.

(42) Long, Y. C.; Zhang, C. H.; Zhou, Y. D. A comparative study for concrete fracture analysissuing smeared-and discrete-crack model. *Eng. Mech.* **2008**, *25*, 80–84.

(43) Li, Y. Q.; Ma, S. Z., *Mechanics of explosion*; Science Press: Beijing, 1992, 57–58.

(44) Chai, J.; Liu, Y.; OuYang, Y. B.; Zhang, D.; du, W. Application of Digital Image Correlation Technique for the Damage Characteristic of Rock-like Specimens under Uniaxial Compression. *Adv. Civil Eng.* **2020**, *2020*, 1–11.