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Research Article

An Innovative Directional Blasting Technique for Coal Mine Exploration and Engineering Testing

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Blasting is a key method of controlling large-area hanging roofs and strong mine pressure in coal mine. The crack propagation direction after blasting has a decisive influence on control effect, and the existing blasting techniques have poor directionality, making it difficult to form a continuous, precise crack. A compound blasting technique (CBT) was proposed; this could achieve a precision, directional crack by using the combination of perforating bullet and explosives, with perforating bullet detonation first and then explosive blasting. The principle of directional crack formation by CBT was studied and a complete set of equipment was introduced, and the effect of continuous directional crack forming was studied experimentally. A CBT test was conducted in Tashan coal mine (Datong mining area): the results showed that a single crack surface was formed in the borehole after the compound blasting, which indicated the desired blasting effect. The CBT improves the accuracy and controllability of fractures and realizes precise directional control of rock strata.

1. Introduction

The mining volume of underground coal seams accounts for more than 80% of the total coal resources mined in China; the underground coal seam mining will inevitably cause movement of the overburden rock, which would trigger coal mine disasters such as ground pressure and water inrush. According to statistics, the number of mine disasters induced by rock migration accounts for 80% of coal mine disasters. Therefore, the strata control is the core and key of underground coal seam mining. Fluidized mining is the development direction of underground coal mining; strata movement and disaster control are the keys to ensure efficient fluidized mining. Blasting is an effective technical means that can control the movement and weaken rock formations due to its powerful and simple process: it is widely used in coal mines.

Zhang revealed the strong mine pressure induced by the breakage of multiple hard, thick roofs and investigated the periodical characteristics and zones in which microseismic (MS) events occurred under multiple hard thick roofs. The deep hole presplit blasting method was used to control the strong ground pressure [1]. Zhang studied the air return roadway failure mechanism of extrathick seams with hard roofs, and the method of deep-hole presplitting blasting was used to reduce the cantilever span over the roadway to good effect [2]. Chen et al. employed deep-hole presplitting blasting to control periodic fractures in thick-hard roof seams, and the deep-hole presplitting blasting on-site implementation reduces thick-hard roof collapse intervals, which show a good control effect on thick-hard roof seams [3]. The hanging up of hard roofs would result in rock burst hazard, and the method of blasting was used to force the roof caving behind the longwall face in Wojtecki's study [4]. Fu et al. simulated the deformation and failure of a hard, thick roof in an island mining face with a large mining height and weakened the hard roofs every 15 m through an advanced deep-hole presplitting blasting technique, which proved to be a success [5]. Gong et al. studied the size of end-mining coal pillar affected by the hard roofs and proposed a method combining presplitting and deep hole blasting to attenuate the abutment stress and reduce the size of supporting coal pillars; a pillar size of 60 m was achieved which improved the rate of coal seam recovery [6]. In addition, such blasting could also be used in the coal seam or overlying hard roofs to improve the coal seam permeability and guarantee gas drainage and safe mining [7, 8]. The existing research indicated that the broken zone and fracture zone in the coal-rock mass were formed by blasting wave, thus reducing the stress concentration in the coal-rock layer and voiding the occurrence of disasters such as rock bursts and gas outbursts. At present, the application of blasting in coal mines mainly focuses on the control of large-area hanging roofs, strong mine pressure in gob-side roadways, and gas drainage.

Although blasting can achieve good results, its control and accuracy are poor, making it difficult to achieve directional, precise presplitting of hard roofs. With the improvement of the control precision of blasting, the application of directional blasting technology in coal mine has gradually become more commonplace. Meng analyzed evolution of main fracture in the shaped charge jet direction and secondary fractures in other directions; results show that shaped charge blasting is able to realize the directional propagation of blasting-induced fractures and release mining pressure [9]. He devised a bilateral energy-gathering tensile blasting technique which achieved directional blasting in rock masses, the device was designed with a tubular shape that allows the borehole to be loaded with explosives, and a line of energy-gathering holes could be arranged in the blasting tube [10], which could achieve directional blasting [11, 12]. Zhang used a PVC plastic slit pipe which could realize good fracture-penetration effect, leaving no obvious fractures in the surrounding rock mass which remained intact during blasting [13]. Yang combined the use of a directional PVC pipe and water gel explosive to achieve the effect of directional blasting, and the technique was successfully applied in the Datong mining area [14, 15]. Yang used a directional fracturing blasting technique for pressure relief of dynamic pressure roadway and achieved a good effect of roadway control [16]; Gao et al. proposed a directional roof split blasting technique and studied the evolution of the blasting-induced damage in the roof rock. These results indicate that the technique could effectively control crack propagation in the roof rock [17]. Li et al. simulated the directional blasting effects by using an empty hole between adjacent blast holes; the results showed that the empty hole had an guiding effect on crack propagation between blast holes and the effect of crack propagation in the direction of blast hole connection [18]; Su et al. studied the directional blasting effects affected by water jet slot, and the directional crack propagation and the blast stress wave transmission were analyzed [19]. Similarly, other scholars have also used similar technical means to conduct directional roof cutting and conducted research on the prevention of strong mine pressure in roadways in coal mines [20–22].

Based on the above research, it can be found that the directional blasting technology in coal mine mainly achieves its directional function by improvement to the assembled piping, which has been preliminarily applied in coal mines to good effect; however, the following deficiencies remain: ① the length of the crack surface is limited after single-hole directional blasting; ② the directional control effect is good, but it is difficult to form a continuous and smooth crack surface; ③ the drilling density and the labour intensity is high during the underground operation. Therefore, it is necessary to propose a new type of directional blasting technique to achieve long-distance directional, continuous, and smooth crack surfaces, while decreasing the number of holes, increasing the spacing between holes, and improving the efficiency and effectiveness of underground blasting operations.

A new type of directional crack-forming technology of CBT was proposed to achieve precise and directional cracks in rock formation by combined use of a perforating bullet and dynamite. The crack surface was continuous, long, and smooth while the blast hole spacing was large and the labour intensity was reduced. CBT can successfully weaken the mechanical characteristics of the hard roof strata overlying the thick coal seam and can effectively reduce the mine pressure appearing at the working face when the high hard strata break. The study of the CBT and its effect of crack formation involved in situ tests in coal mines to verify the directional crack-forming effect.

2. Directional Crack Forming by CBT

The directional crack-forming technology by CBT was achieved by using perforating bullets and dynamite and mainly consisted of an assembly pipe, perforating bullet, dynamite, and detonating cord, in which the assembly pipe was used to assemble the perforating bullet and dynamite, as shown in Figure 1. In order to ensure the installation efficiency and the safety, the pipes are made of PVC with flame retardant and antistatic materials.

In specific applications, the perforating bullets are installed on the assembly pipe at regular intervals. The interval is related to the surrounding rock property, drilling depth, and jet intensity of perforating bullets. The shape of the perforating bullet is a cone, and a stream of metal particle flow (MPF) delivering a high-impact load is formed during blasting. The jet direction of adjacent perforating bullet can be the same as, or opposite to, the impact and dynamite is used to fill the gap between two adjacent perforating bullets.

In the operation of CBT, the perforated bullets were firstly motivated to form a jet by the detonating cord, and some jet channels were formed by the MPF on the hole wall (Figure 2(a)). The channel made by MPF was divided into four continuous processes (Figure 2(a), (i) to (iv)).

Figure 2(a) (i) shows that the MPF jets from the bottom of perforated bullets to the hole wall and continuously stretches its length during the movement. Figure 2(a) (ii) illustrates the moment the MPF strikes the hole wall. At this point, the pressure, temperature, and velocity of the MPF reach a maximum and a shockwave is injected to the hole wall through the contact point. Meanwhile, the hole wall imparts via the MPF a reflected shockwave and a rarefaction wave, and some of the metal particles are piled up at the entrance, while the remainder are ejected. Figure 2(a) (iii) demonstrates that the MPF continuously strikes the hole

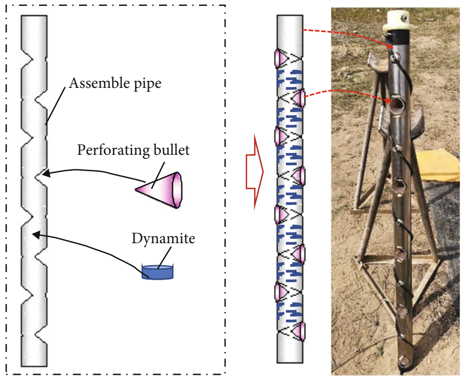


FIGURE 1: Assembly drawings of perforating bullets and dynamite.

wall, and the perforation hole is gradually deepened. Figure 2(a) (iv) shows that a discontinuous state of the MPF. When the speed is below a certain critical value, the impact strength of the MPF is greatly reduced, and the jetting process ends.

CBT enters the second stage at the microsecond level of detonation igniting interval time after the formation of the precrack hole by the perforated bullets. The second stage of CBT is to achieve a directional crack by way of the high-energy gas (Figure 2(b)). The perforating bullet instantly generates high-temperature, high-pressure gas while jetting, which detonates dynamite between the perforating bullets, thus producing a larger amount of high-pressure gas. The high-energy gas expands in the drilling hole and perforation channel, which will generate stress concentration along the hole and perforation channel.

According to the theory of fracture mechanics, when high-energy gas is squeezed into the perforation channel, a stress concentration is generated at the tip of the crack. Once the stress concentration reaches a certain level, that is, when the stress intensity factor generated by the stress at the end of the crack is larger than dynamic fracture toughness of the rock, the crack starts to expand; otherwise, the crack stops. The crack expansion is shown in Figure 3, and the stress intensity factor at the crack tip is

$$K_I = PF(\xi)\sqrt{\pi(r+a)}, \tag{1}$$

where P is the pressure exerted by the explosive gas in the blast hole, r is the radius of the blast hole, a is the crack length, and $F(\xi)$ is the correction factor related to r and a, $\xi = (r+a)/r$.

When the stress intensity factor K_I near the crack tip is greater than or equal to the dynamic fracture toughness of the rock K_{Id}, the crack begins to destabilise and expand, forming burst cracks. The criterion for the initial state of crack propagation is

$$K_I = PF(\xi)\sqrt{\pi(r+a)} \ge K_{Id}, \tag{2}$$

where K_{Id} is the dynamic fracture toughness of the initial rock, the greater the value of K_{Id}, the greater the ability of the rock material to resist fracture; this is an inherent property of the material and can be tested by experiment. From Equation (2), we get

$$P \ge \frac{K_{Id}}{F(\xi)\sqrt{\pi(r+a)}}. \tag{3}$$

It is not difficult to find from Equation (3) that assuming that K_{Id} of the rock medium remains constant, then as the crack length a increases continuously, the required driving pressure decreases. With the continuous influx of high-energy gas, the crack will expand without restriction at an accelerated rate. The actual situation is such that the development of the cracks stopped shortly afterwards, mainly because the explosion gas pressure had not remained constant. In engineering practice, when the explosive gas is wedged into the crack, as the contact surface between the gas and the rock medium increases in area, the gas temperature will decrease rapidly due to heat exchange, and its volume will increase due to the increased number of cracks in the rock, which makes the pressure of explosive gas decrease rapidly.

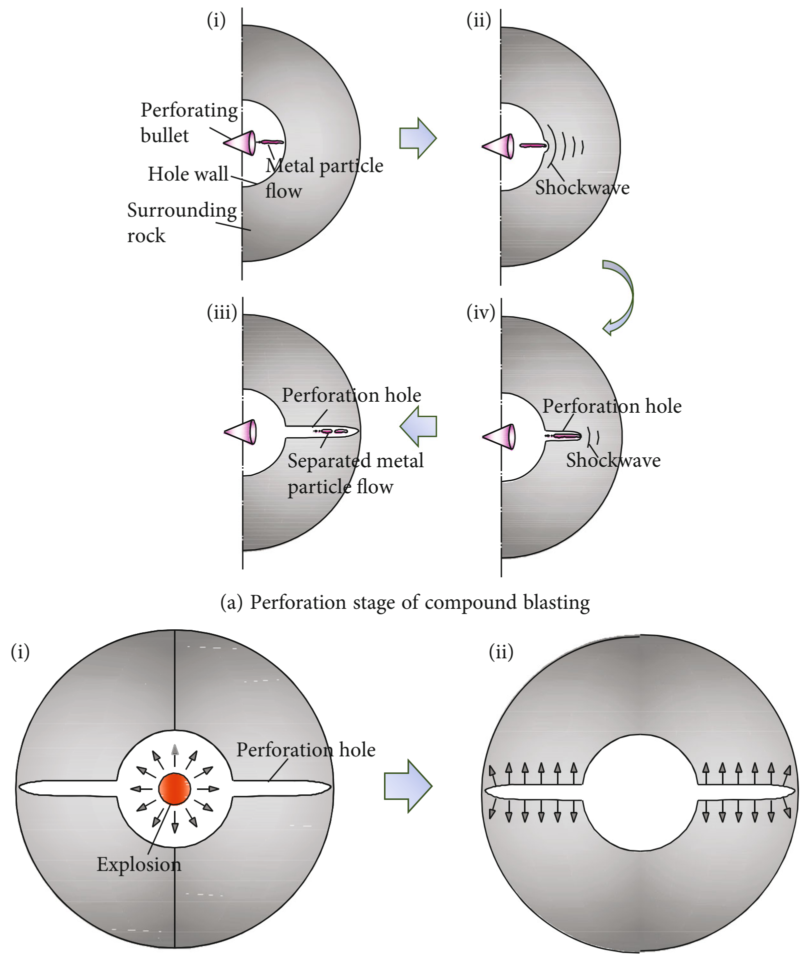
When the burst pressure $P < K_{Id}/F(\xi)\sqrt{\pi(r+a)}$, that is, when the driving force generated by the burst pressure does not meet the fracture condition, the crack stops expanding. It can be seen from Formula (3) that when the perforation process is performed firstly, the length of "a" can be increased, so the expansion pressure of the crack can be reduced, and the expansion time and length of the crack can be increased. Therefore, the process of CBT can not only realize the precise directional expansion but also increase the expansion length of the crack.

3. The Test of Compound Blasting Directional Crack-Forming Effect

3.1. Experimental Design of Directional Crack-Forming Effect. A compound blasting test was conducted to study the crack-forming effect of CBT and provide guidance for underground application in coal mines. Referring to the physical and mechanical parameters of the underground rock mass, a concrete target with a diameter of 5 m and a height of 1.4 m was poured on the ground using cement and quartz sand (0.125 mm) in a proportion of 1 : 1, and drilling holes were constructed in the concrete target with a hole spacing of 1.5 m (Figure 4). The assembly pipe, perforating bullets, and dynamite were used to assemble compound perforating equipment, to simulate the perforation and blasting process of CBT and verify the crack extension in adjacent holes.

The specific test process is as follows.

① Assembly of the compound blasting device: we put a 1-meter-long assembly pipe (Φ 51 mm diameter) into a single drilling hole, and ten perforating bullets were loaded and the dynamite in-filled between the perforating bullets. Two adjacent boreholes (1.5 m apart) were selected for the test (other boreholes will be used according to required test conditions)



(b) Secondary fracturing stage of compound blasting

Figure 2: The process of compound blasting.

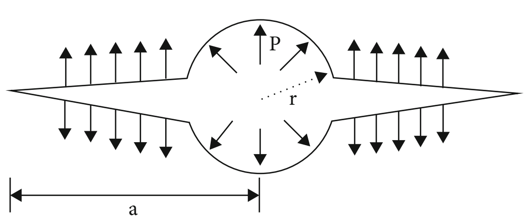


Figure 3: Schematic representation of fracture extension.

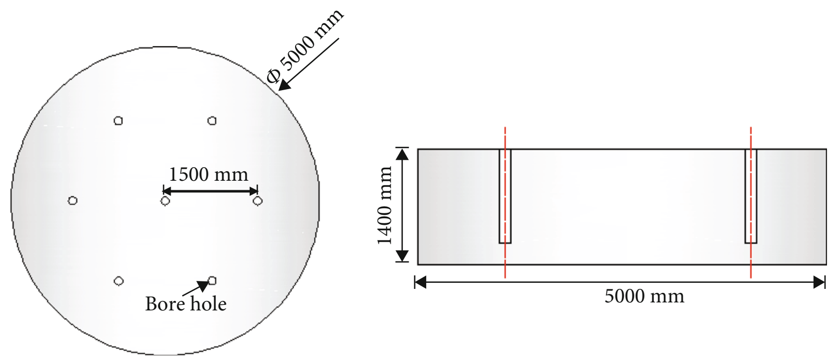
② We placed a 10-millimeter-thick steel plate at the bottom of the borehole and put the assembled composite blasting instrument into the drilling hole. The detonator line was led out from the top hole, and then, the hole was filled with quick-setting cement, and the top of the concrete target was compacted with sand bags

③ We used a dynamic high-speed camera to record the blasting process and used a dynamic instrument to measure dynamic changes in pressure along the borehole during the crack-forming process

④ After blasting, the borehole spying instrument was used to observe the crack-forming effect along the inner wall of the borehole and determine whether to conduct the next group of tests according to the effects observed

The requisite test consumables are listed in Table 1.

3.2. Test Results. The results of the compound blasting test are shown in Figure 5. After the compound blasting, a continuous splitting surface formed along the two drilling directions. Due to the low confining pressure in the specimen and the large blasting energy, the specimen was broken to a greater extent after blasting, and the splitting surface was not that flat. As can be seen in Figure 5(a), the perforating channel formed by the perforating bullet was visible, and the channel length reached 0.5 m. After the secondary blasting, the high-energy gas further split along the perforation channel, forming a directional continuous crack surface between the two boreholes. The distance between the two sides of the borehole and the specimen edge was 1.5 m, and the length of the perforation on both sides was 0.5 m; however, the confining pressure on the specimen was relatively low, and combined with the effect of the directional splitting of the compound blasting energy, the crack penetrated the specimen along the connecting direction of the two blast holes.



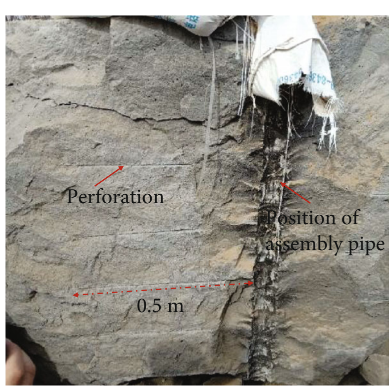
(a) Specimen size

(b) Specimen size

Figure 4: Compound blasting directional crack-forming test.

Table 1: Test consumables.

Equipment	Specification	Number of tests	Testing hole
Two ∅51 mm assembly pipes	2 × 1 m length	Not less than once	Two drilling holes, at 1.5 m spacing, ∅75 mm, 1.4 m depth
Perforating bullets	RDX 25 g × 10		
Dynamite	120 g × 20		



(a) Single-hole blasting effect

(b) Double-hole blasting connection effect

Figure 5: Ground test of compound perforating blasting operations.

The test results confirmed the feasibility of directional crack forming by CBT. The perforation channel provided a guarantee for the connection of fracture surface, and finally the length of directional crack was greater than that of the perforation channel; because the length of the assembly pipe was 1 m and the height of the specimen was 1.4 m, the sealing length was limited to 0.2 m in the top and the bottom, dissipating blasting energy from the orifice, as illustrated in Figure 5(b). Due to the limited test conditions, the underground working conditions cannot be completely simulated, and the length of the sealing section is short, which leads to some energy loss. In addition, the absence of confining

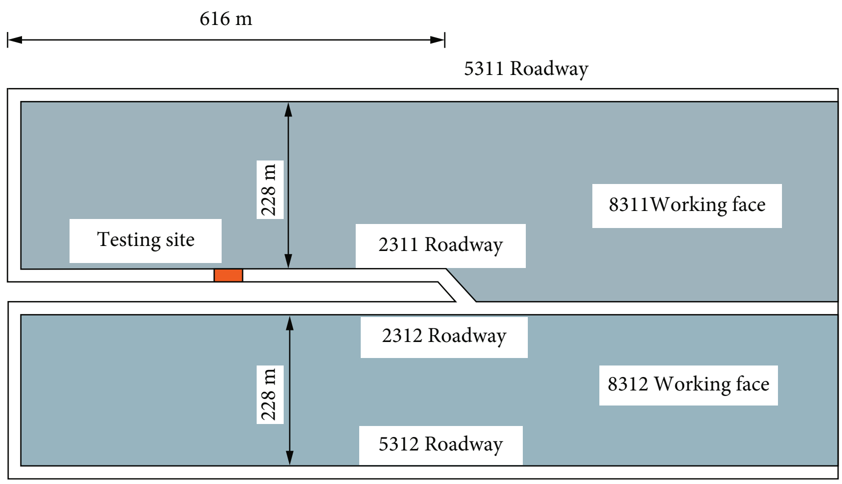


Figure 6: Working surface (plan).

Column	Lithology	Thinkness/m	Remarks
	Mudstone	4.4	Main roof
	Medium grained sandstone	6.5	
	Mudstone	2.4	
	Medium grained sandstone	1.6	Immediate roof
	Sandy mudstone	2.5	
	Mudstone	3.3	
	Coal	3.4	Coal seam

Figure 7: Prevailing geological conditions.

pressure around the specimen also leads to a longer crack propagation length, but the uniformity of the crack is not affected. However, to verify the effect of crack propagation after CBT, an industrial test was carried out.

4. Field Application

4.1. Coal Mine Situation. The 8311 working face of the Tashan coal mine in the Datong mining area was 228 m long, with a strike length of 616 m and a minable length of 590 m. The 8312 working face was 228 m long, with a minable length of 714 m, as shown in Figure 6. The 8311 working face was firstly mined, in order to increase the recovery rate of coal resource, only a 6.0 m small coal pillar was left between the 8311 and 8312 working faces. The 4# coal seam was mainly mined in 8311 and 8312 working faces, with a maximum surface elevation of 1526 m, a minimum elevation of 1415 m, and a working face elevation of 993-1010 m. The thickness of the coal seam is 3.20-3.60 m, and the average thickness is 3.40 m. The hard, complete, thick rock layers present in the roof of the 8311 working face, and the immediate roof of the 4# coal seam mainly consists of three layers of mudstone, sandy mudstone, and medium-grained sandstone, and main roof consists of three layers of mudstone, medium-grained sandstone, and mudstone (Figure 7).

The hard, thick rock layers in the roof of the 8311 working face make it easy to form a large hanging roof in the gob side lateral roadway during the mining process of the 8311 working face. Due to the rotational deformation of the overhanging roof beam and the overburden pressure, the support load on the 2312 roadway will be greatly increased, causing significant deformation and instability of the rock around the roadway, even resulting in disaster. The hard roofs not only fail to fall timeously and completely but also may form a permanent cantilever structure, increasing the load on the coal pillar, increasing deformation of the 2312 roadway, thus affecting the stability of the surrounding rock.

4.2. Field Application Design. Due to the dense interlayers of the hard roof overlying the working face, the thickness of the interlayer varies with adverse effects on the roof cutting and pressure release associated therewith. The effect of conventional roof cutting methods is poor, the cut-through rate is low, and the cutting surface is uneven; a large hanging roof

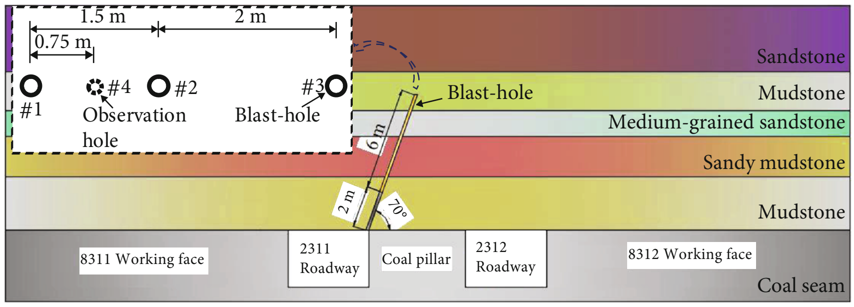


Figure 8: Blast hole layout (plan).

produces a large additional force in the gob side lateral roadway. Compared with conventional roof cutting, the CBT can achieve continuous and smooth crack surfaces; therefore, the CBT was used to cut the hard roofs in a certain direction by forming a directional crack, so that the roof can collapse in a predetermined direction.

A directional cutting roof scheme was designed using in the 8311 working face. On 10 January 2019, three boreholes were arranged in the 2311 roadway for testing, the borehole spacing was 1.5 m and 2.0 m, respectively, the diameter of assembly pipe was 50 mm, the diameter of the borehole was 75 mm, the depth of borehole was 8 m, and the angle to the horizontal plane was 70°. The length of perforated section was 6 m, and the length of the sealed section was 2 m (Figure 8).

4.3. Application Results. By inspection of the blast holes, the blast crack can be obviously seen: the crack rates in no. 1 blast hole, no. 2 blast hole, and no. 3 blast hole were 91%, 89%, and 61%, respectively (Table 2, Figure 9(a)).

To observe the penetration between the adjacent holes after directional blasting, an observation hole with a diameter of 32 mm and depth of 8 m was drilled in the centre of no. 1 blast hole and no. 2 blast hole. Through visual inspection, it was found that the connectivity rate between the holes was low, and a continuous slit could not be formed, which showed that the directional effect by the CBT was not ideal (Table 3, Figure 9(b)).

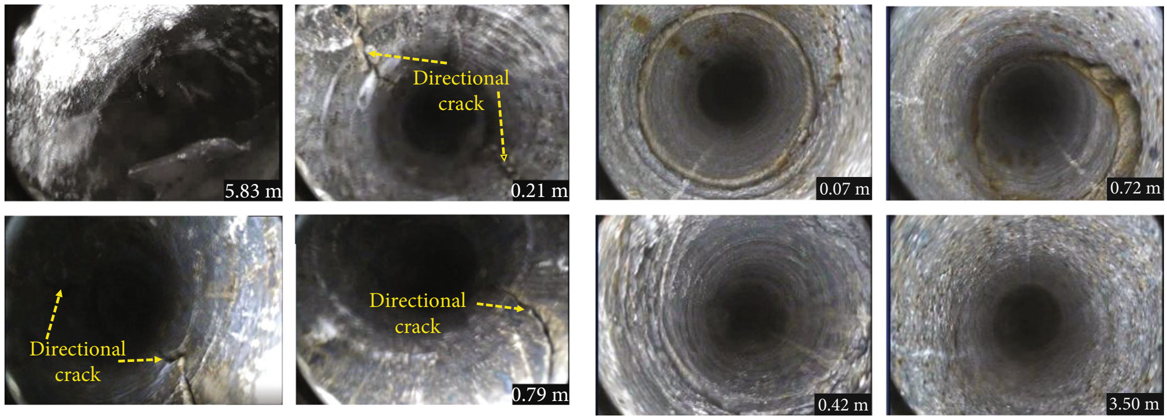
There are two main reasons for the poor connectivity between the two adjacent holes: due to the good directional properties of CBT, a single crack surface is formed after blasting. If the directional phases of two adjacent blasting holes are not in the same plane, the crack surfaces after blasting cannot connect effectively. In addition, the diameter of the observation borehole was too small to allow observation of the degree of development of the crack surfaces on both sides; during the compound blasting process, the detonation energy is large, and the sealing distance of 2 m is short, which leads to a certain energy leakage, and the length of the fracture surface was thus limited, resulting in the crack surfaces of adjacent boreholes not being communicated effectively after blasting. Due to the complexity of the underground environment, there are many technical problems to ensure the connectivity of blasting crack. Therefore, when operating on site, it is necessary to ensure that the blasting crack direction in the blast hole is in the same plane, and secondly, ensure that each process such as blasting and sealing meets the requirements.

Table 2: Observation of the effects of blast hole formation.

Blast hole	Crack section (m)	Crack distribution rate
#1	0.00~2.00	91%
	2.46~5.20	
#2	0.00~2.35	89%
	2.89~5.21	
#3	0.00~1.87	61%
	2.08~2.70	
	3.01~3.30	
	4.25~4.97	

5. Discussion

Due to the high strength and large breaking step of the hard roofs, the mine pressure remained high during breaking of the hard roofs, hindering safe and efficient mining. Explosive blasting is powerful and can weaken the roof yet achieve efficient control thereof, making it popular for use in coal mines. At present, there are various ways to use explosives in coal mines: random blasting, wherein the use of explosives is relatively simple. Generally, the explosive is directly loaded into the charging tube and detonated by the detonator. Blasting of explosives has no directionality, and the blasting energy radiates from the centre to the surrounding mass, forming a fracture zone, crack zone, and vibration zone (Figure 10); the specific damage range is related to explosive charge, the strength of the surrounding rock, and the triaxial state of stress. The other method entails directional blasting by loading dynamite into charge tube, but compared with the random blasting method, the difference is that the structure of the assembly pipe is modified so that the dynamite can be clustered along a predetermined direction after blasting, thus achieving directional blasting. At present, the energy-concentrating tube string structure mainly used has three types as shown in Figure 10(b), all of which can realize the directional function through the modification of the tube string structure [10, 15, 16]; however, due to the noncoupling charge of the dynamite and pipe string, the directional blasting effect of this directional blasting method needs to be further improved. The length

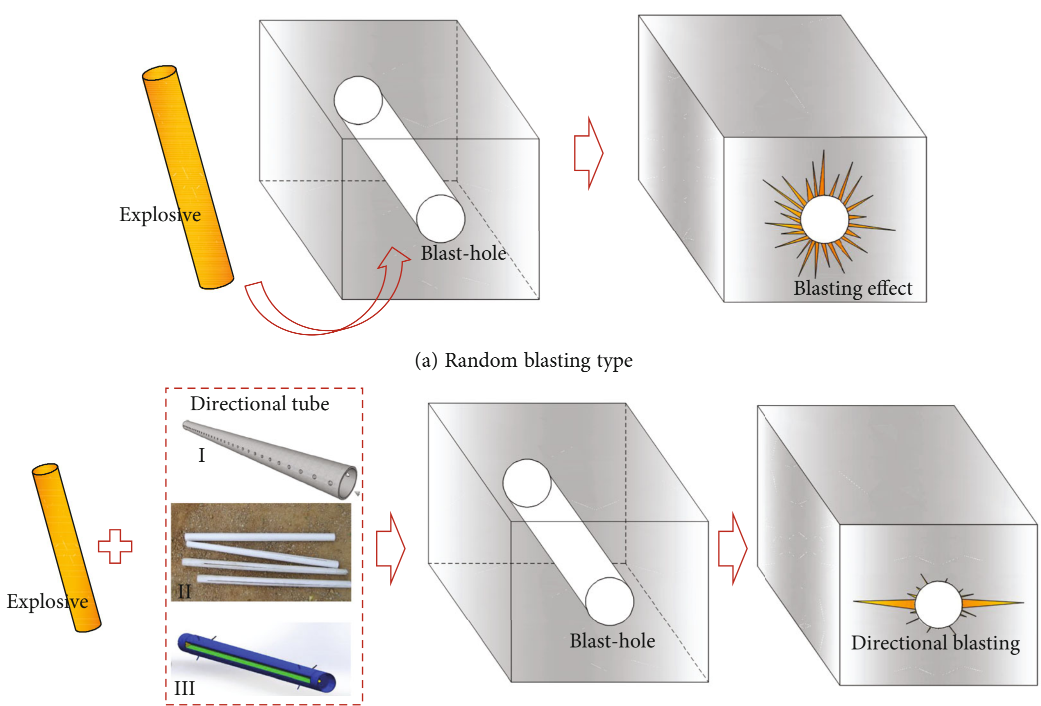


(a) Blast hole views (b) Observation hole #4 views

FIGURE 9: The observation of blast hole and #4 hole.

TABLE 3: Results of drilling inspection.

Hole number	Transverse fissure	Longitudinal fissure	Connectivity rate
	0.07 m (1 cm)	0.1~0.5 m	8%
#4 observation hole	0.072 m (2 cm)	0.72~0.8 m	
	4.03 m (2 cm)		
#5 observation hole	0.42 m (1 cm)		2%



(a) Random blasting type

(b) Directional blasting type

FIGURE 10: Blasting method and its effect diagram.

of directional fracture surface is limited, and the borehole spacing is small and the borehole density is large in practice.

The proposed CBT method used a perforating bullet and dynamite in tandem: the perforating bullet blast and jet act within microseconds to form a directional jet channel. Dynamite blasting at the millisecond level forms high-temperature, high-pressure gas and continues to blast along the jet channel for secondary blasting, thus forming a

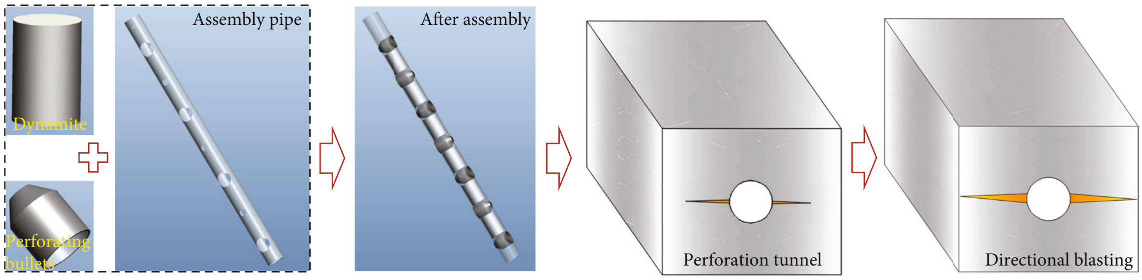


Figure 11: Process of the CBT.

continuous directional crack surface. The jet channel formed by perforating bomb blasting determines the direction for the formation of the continuous crack surface (Figure 11).

The factors that affect the length of crack surface mainly include the jet depth by the perforating bullet, the energy of secondary blasting of dynamite, and the conditions of the surrounding rock. The final crack length increases with the increase of jet depth; the greater the jet depth, the greater the crack surface length. Similarly, the greater the energy of secondary blasting of dynamite, the greater length of crack; because of the effect of secondary blasting of dynamite, the final length must be greater than that of the jet. In addition, the strength of the surrounding rock and the ground stress environment in which the blasting operation takes place also have direct influences on the crack length: the larger the strength of the surrounding rock, the greater the in situ stresses, and the smaller the fracture length.

CBT, as a new type of directional crack-forming technology, has achieved good effects in coal mine application for the first time, but it still needs improvement in many aspects. Firstly, the efficiency of assembly should be improved. The main processes involved in CBT are drilling, dynamite assembly, loading drilling, sealing, and blasting. The process of assembling perforating bullets is time-consuming owing to the particularity of the perforating bullet structure, the jet can only expand in one direction, and the assembly of perforating bullet needs to be determined according to the direction required. Secondly, the order of assembly of perforating bullet and explosive requires attention: one of the characteristics of CBT is that dynamite is used to fill the gap between two perforating bullets, so we should pay attention to the sequence in the assembly process, taking time. Finally, there is relationship between the amount of perforating bullet and dynamite. Blindly increasing the amount of explosive can increase the length of the crack, but it will also increase the difficulty of sealing the hole. Therefore, we should choose an appropriate type of perforating bullet and a suitable amount of dynamite, and the optimal borehole spacing should be determined accordingly to achieve the effect of continuous directional crack forming.

The underground strata in a coal mine is a “black-box,” and the morphological characteristics of the broken rock strata directly affect the mine pressure in the stope, and the realization of precise directional control of the rock strata is the key to solving the problem. The development of CBT upgrades the traditional random blasting to directional blasting, which realizes the directional expansion of cracks and the precise control of strata structure. The paper only studies the effect of the directional crack-making of CBT, and an in-depth research on key issues such as technical parameters and crack-making will be continued in the next, to continuously improve the development of CBT.

6. Conclusions

(1) A new type of directional crack-forming technology by CBT was proposed for use in fluidized mining. The perforating bullet and dynamite were used in tandem: the perforating bullet was blasted to form a perforation channel on the hole wall, and secondary blasting of dynamite produced high-energy gas that expands along the perforation channel to achieve the desired directional crack-forming function in the rock stratum

(2) A concrete target with a diameter of 5 m and a height of 1.4 m was poured on the ground to explore the effect of directional crack forming by CBT. It was found that the length of the perforation channel could reach 0.5 m, and the directional crack surface formed by blasting split the concrete target

(3) A CBT test was conducted in Tashan coal mine, and the results showed that a single directional crack surface was produced in the blast hole, and the crack surface was evenly distributed along the whole drilling direction, indicating the feasibility of CBT. It can be popularised and applied in directional control of hard roofs in coal mines and improve the efficiency and accuracy of control of hard roofs

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflict of interest.

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