Field application of non-blasting mechanized mining using high-frequency impact hammer in deep hard rock mine

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Abstract: A non-blasting mechanized mining experiment was carried out with a high-frequency impact hammer, and the daily mining performance was recorded to explore the applicability of the high-frequency impact hammer in deep hard rock mines. Before the field application, the scope of the excavation damage zone was monitored, and rock samples were obtained from the ore body to be mined to carry out a series of laboratory experiments. Field application results show that the overall excavation efficiency reaches 50.6 t/h, and the efficiency of pillar excavation after excavating stress relief slot reaches 158.2 t/h. The results indicate that the non-blasting mechanized mining using high-frequency impact hammer has a good application in deep hard rock mines, and the stress relief slot is conducive to mechanical excavation. In addition, the high-frequency impact hammer also exhibits the advantages of high utilization rate of labor hours, small lumpiness of spalling ore, little dust, and little excavation damage. Finally, according to the field application and laboratory experiment results, a non-blasting mechanized mining method for hard rock mines based on high-frequency impact hammer is proposed.
Key words: hard rock mine; non-blasting mechanized mining; high-frequency impact hammer; excavation damage zone; stress relief slot; mining method

1 Introduction

With the mining depth getting deeper and deeper, the severe disturbance caused by the drilling and blasting method has an increasing impact on mining safety [1−4]. For this reason, non-blasting mining methods including mechanical cutting have been proposed, and can gradually replace the drilling and blasting method [5−9]. The mechanical cutting equipment can transfer energy from the hydraulic pump to the rock breaking tools, and then to the rock, which can complete the rock breakage with high quality and low disturbance [10,11]. At present, the more extensive mechanical excavation equipment used in mining and civil engineering includes roadheaders, tunnel boring machines

(TBMs) and impact hammers [12−15]. Road-headers are mainly used in mining and civil construction industry due to their good flexibility and maneuverability [16−18]. However, as limited by the severe wear caused by the friction between the cutters and the rock, the roadheader is more difficult to excavate the hard rock [18−20]. Therefore, for metal mines with hard rock as the mainstay and high integrity, the excavation effect of the roadheader still needs to be explored [21]. Disk cutters are installed on the cutterhead of TBM, which can break medium to extremely hard rocks [22]. Although TBMs are widely used in tunnel excavation due to their advantages of fast construction speed and small excavation disturbance, it is not practical to apply them in hard rock mining due to their big body and high cost.

Hydraulic impact hammers also have a wide range of applications. The rock breakage of the hydraulic impact hammer is achieved by high-frequency cyclic mechanical impact, which has a significant effect when crushing highly fractured rocks. As a component on the excavator, the hydraulic impact hammer converts hydraulic energy into mechanical impact energy [23].

In order to apply non-blasting mechanized mining to hard rock mines, it is necessary to improve the rock cuttability that is affected by cutting tools and rock properties [1,24−26]. Through rock indentation experiments on intact, fractured and defective rock samples, it is found that rock defects such as boreholes will change rock intactness and improve rock cuttability [15]. The high stress of rock mass in deep mining also has an important effect on rock cuttability [27,28]. When the rock is under biaxial confining stress, uniaxial confining stress and no confining stress condition, the rock cuttability increases successively. Among them, the rock cuttability first decreases and then increases with the increase of uniaxial confining stress [4,15,29]. On the other hand, however, high stress, which severely affects the rock cuttability, is also regarded as a factor that can turn harm into profit to promote non-blasting mechanized mining [28]. When the orebody is under high stress, stress redistribution will occur after proper induction engineering is excavated, which will promote the development of fractures and form an excavation damage zone (EDZ). Our previous researches used roadheaders to carry out non-blasting mechanized mining. The results showed that the roadheaders had good cutting efficiency, but it was difficult to excavate extremely hard rock, and the picks were seriously worn [4,30]. The high-frequency impact hammer can apply static load and high-frequency vibration to the ore rock, which can not only make the fractures in rock connected to spall the ore rock, but also have a good effect when crushing extremely hard rock.

In this study, the scope of EDZ was monitored and a non-blasting mechanized mining test using high-frequency impact hammer was carried out to further explore the application of non-blasting mechanized mining in deep hard rock mines. In the process of field application, the mining performance such as the mined ore volume was recorded to measure the applicability of the high-frequency impact hammer in hard rock mining. In order to release the stress in the vertical direction, the stress relief slot was excavated, and the influence of the stress relief slot on mining was explored. With regard to the existing rock breaking equipment, the application of non-blasting mechanized mining in hard rock mines requires reasonable and efficient use of the EDZ and stress relief slots to improve the rock cuttability. Finally, based on field application, laboratory test results and theoretical analysis, a non-blasting mechanized mining method based on high-frequency impact hammer is proposed.

2 Mining schemes

As a conventional rock breaking tool in civil engineering, impact hammers have the advantages of good crushing performance, high energy utilization and direct installation on excavators, and were also commonly used in mining operations. The existing excavators and high-frequency impact hammer in the mine were modified to be suitable for mining, and the bucket teeth was installed at the tip of the impact hammer, which can apply static load and high-frequency impact. The high-frequency impact hammer mounted on the excavator is shown in Fig. 1.

Field application of non-blasting mechanized mining using a high-frequency impact hammer was carried out in Maluping Mine in Guizhou Province, China, which has gradually entered the stage of deep mining. In consideration of linking the field application with normal mine production to form a systematic mining and transportation process, a stope at the altitude of 490 m (the actual buried depth over 1000 m) was prepared. By excavating preparation and cutting entryways, a peninsula-type pillar was formed, and the stope is shown in Fig. 2.

Before the field application, cores were drilled from the roof, ore body, and floor by geological drilling. Some of the relatively complete cores were processed into cylindrical specimens to carry out uniaxial compressive tests and Brazilian splitting tests. However, due to the development of fractures in the pillars, cores drilled from ore body were completely broken during processing, which shows the feasibility of non-blasting mechanized mining to a certain extent. In order to measure the rock

properties of the pillars accurately, large-size ores peeled off the ore body were prepared for rock breakage using a point-attack pick. The difficulty of rock breakage can be measured by peak cutting force (PCF) and specific energy (SE), which were obtained and calculated from load−displacement curve of rock fragmentation. The preparation of the rock samples is shown in Fig. 3, and the basic mechanical tests and rock fragmentation using a point-attack pick test results are given in Table 1 and Table 2, respectively. According to the above tests, it can be known that the uniaxial compressive strength (UCS) values of the intact rock in roof and the broken roof are about 117 and 49 MPa, respectively. The Brazilian tensile strength (BTS) values of the rock in roof and the floor are about 8.6 and 6.5 MPa, respectively, and the UCS of the rock in floor reaches 187 MPa. For intact orebody, the PFC of 28.31 kN can break the ore sample, and its SE is 0.0653 J/cm^3. When carrying out rock fragmentation using a point-attack pick on ore sample containing boreholes, it can also be completely split under PCF of 28.68 kN, and its SE is even smaller below 0.007 J/cm^3. When there are

Fig. 1 High-frequency impact hammer mounted on excavator: (a) Excavator; (b) High-frequency impact hammer; (c) Bucket teeth
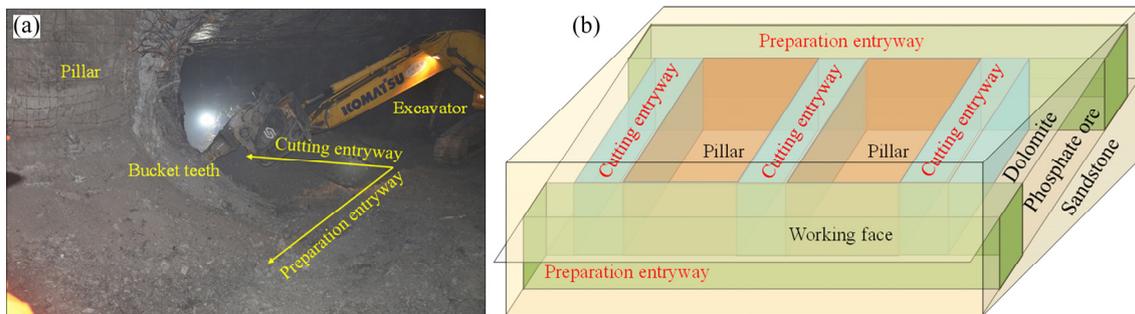

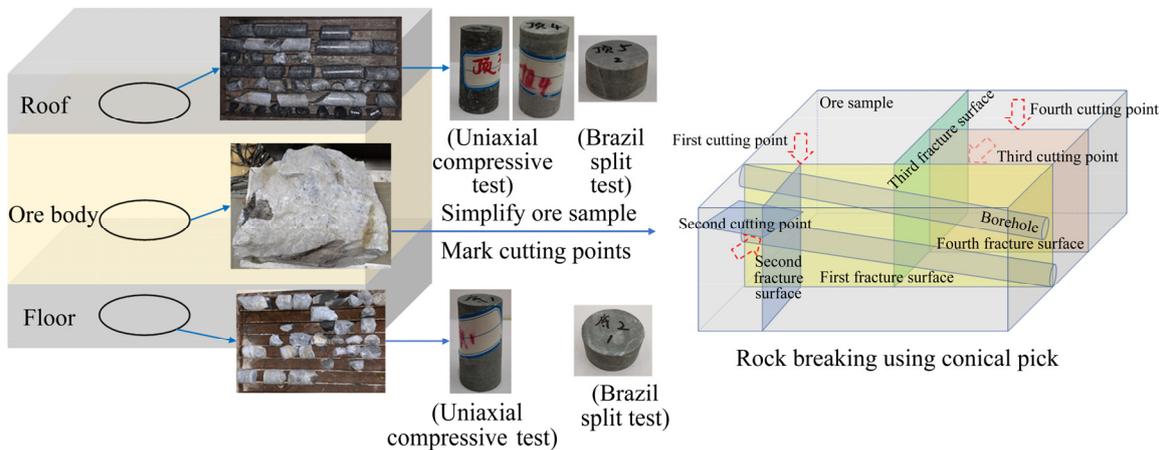**Fig. 2** Field mining stope: (a) Field situation; (b) Model of pillar

Fig. 3 Preparation of rock samples

Table 1 Basic mechanical test results

Sampling location	No.	Test result
Roof	R_{U1}	UCS=117.17 MPa
	R_{U2}	UCS=48.67 MPa
	R_{B1}	BTS=8.62 MPa
Floor	F_{U1}	UCS=176.5 MPa
	F_{B1}	BTS=6.48 MPa

Table 2 Rock fragmentation using point-attack pick test results

Sampling location	No.	Test result	Failure image
Ore body	O_{R1}	PCF=28.68 kN SE=0.0070 J/cm^3	
	O_{R2}	PCF=12.36 kN SE=0.0068 J/cm^3	
	O_{R3}	PCF=10.59 kN SE=0.0018 J/cm^3	
	O_{R4}	PCF=28.31 kN SE=0.0653 J/cm^3	

boreholes and fissures in the orebody, the PCF required for rock breaking is only 12 kN with the SE of 0.0018 J/cm^3. The rock fragmentation results above show that when there are defects such as fissures and boreholes in the rock, the PCF and SE required for rock fragmentation decrease, and the rock cuttability increases, which proves the feasibility of non-blasting mechanized mining in hard rock mines to a certain extent.

Different from the drilling and blasting method, the non-blasting mechanized mining using a high-frequency impact hammer has a relatively small range of action and needs to be advanced in a certain order on the working surface. Therefore, three schemes as shown in Fig. 4 were designed prior to on-site mining. Among them, the excavation of the stress relief slot can transform the uniaxial confining stress condition of the pillar into non-confining stress condition, which will reduce the peak cutting force required for rock crushing and improve mining efficiency. However, the left−right reciprocating mining requires the excavator to move continuously, which causes the requirement of a larger working space and increases running time. After comprehensive consideration, bottom-up reciprocating mining after excavating the stress relief slot will be adopted in the field application.

3 Field monitoring of excavation damage zone (EDZ)

When the roadways are excavated, the horizontal stress in the surrounding ore body will be released, and stress concentration will be generated in the vertical direction, which will promote the development of fractures. The area where the cracks develop, and the rock is broken around the opening is called the EDZ. LI and GU [31] proposed that EDZ should be formed by excavating suitable induction engineering to improve the cutability of hard rock. To verify this conceive, a non-blasting mechanized mining test was carried out after excavating the induced roadway, which proved the feasibility of non-blasting mechanized mining after high geostress induced fracturing [32]. Therefore, the distribution of EDZ areas of the pillars induced by excavation is a key factor in determining the non-blasting mechanized mining. In order to clarify
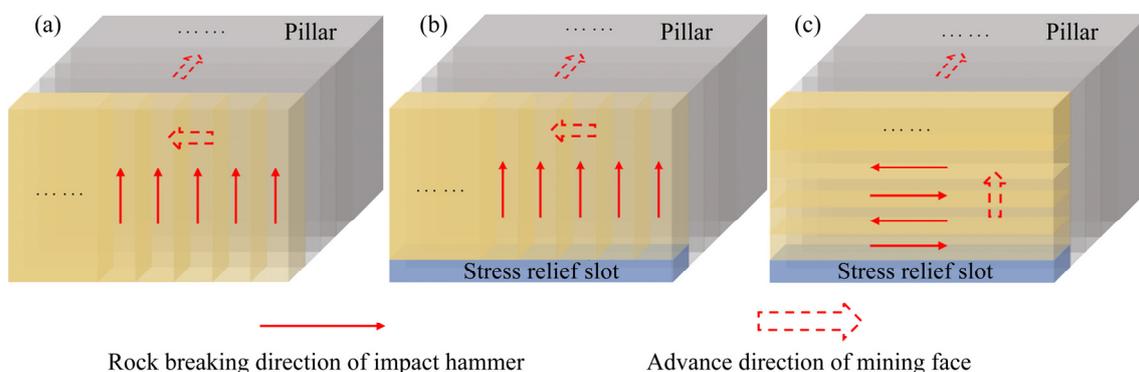

Fig. 4 Field mining schemes, including bottom−up reciprocating mining without excavating stress relief slot (a), bottom−up reciprocating mining after excavating stress relief slot (b) and left−right reciprocating mining after excavating stress relief slot (c)

the thickness of EDZ and determine the excavation scope to improve mining efficiency, the field monitoring of the EDZ was conducted before the field application.

A total of 18 monitoring holes with a depth of 3.5 m and a diameter of 73 mm are evenly distributed on the three free surfaces of pillar, and the distribution of monitoring holes is given in Table 2. The monitoring hole is parallel to the horizontal plane, and there is no gravel or stagnant water in the hole to ensure that the monitoring equipment can take the image of the hole wall smoothly and clearly. The monitoring equipment is advanced with high-definition drilling television, which can record hole wall images at different depths. The monitoring equipment is shown in Fig. 5.

The digital images are embedded into the image analysis software which can form a digital core showing hole wall images at different depths, and the monitoring hole digital core images are shown in Fig. 6. The boundary of the EDZ is the contact surface between the original intact and fractured rock masses caused by stress redistribution. By identifying and characterizing the cracks displaying in the monitoring hole wall images, videos and digital cores, the thickness of the EDZ at each monitoring hole can be determined. The actual thickness of the EDZ is the monitored EDZ thickness in the monitoring hole and the thickness of the hole collapse caused by drilling. The monitoring results and the distribution of the EDZ are given in Table 3.

According to the monitoring results, the thickness of the EDZ is between 1.92 and 3.41 m, and the average thickness is 2.59 m. Therefore, the cutting step should be less than 2.59 m to ensure that the ore mining is within the EDZ to meet the needs of non-blasting mechanized mining. When the ore body within the EDZ is mined, the mining equipment will be transferred to the nearby stope to continue mining. The excavated pillar will form a new EDZ after a period of time under the action of stress redistribution. In order to maximize the use of EDZ induced by excavation, it is necessary to determine the formation law of EDZ in further research, so as to accelerate the secondary formation of EDZ through excavation induced roadway and artificial disturbance. The No. 1 monitoring hole is the closest to the working surface and has the largest thickness of the EDZ. The No. 6 monitoring hole, which is far away from the working surface, has the smallest thickness of the EDZ. These findings indicate that the pillar is affected by disturbance of rock breaking, which will promote the development of fractures in the pillar and expand the range of the EDZ. This also verifies the feasibility of promoting the formation of EDZ through artificial disturbance.

4 Field mining progress

Field application of non-blasting mechanized mining was conducted from 28 September to 29 October, 2020. Due to monitoring tasks and equipment failures, the actual mining time was 7 days. During the field application, the state of mining was recorded, which includes daily mining
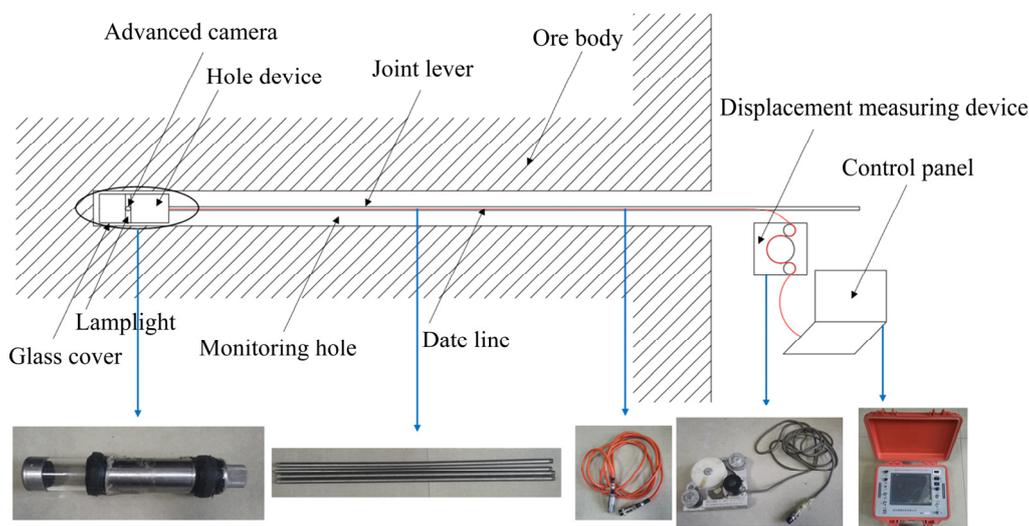

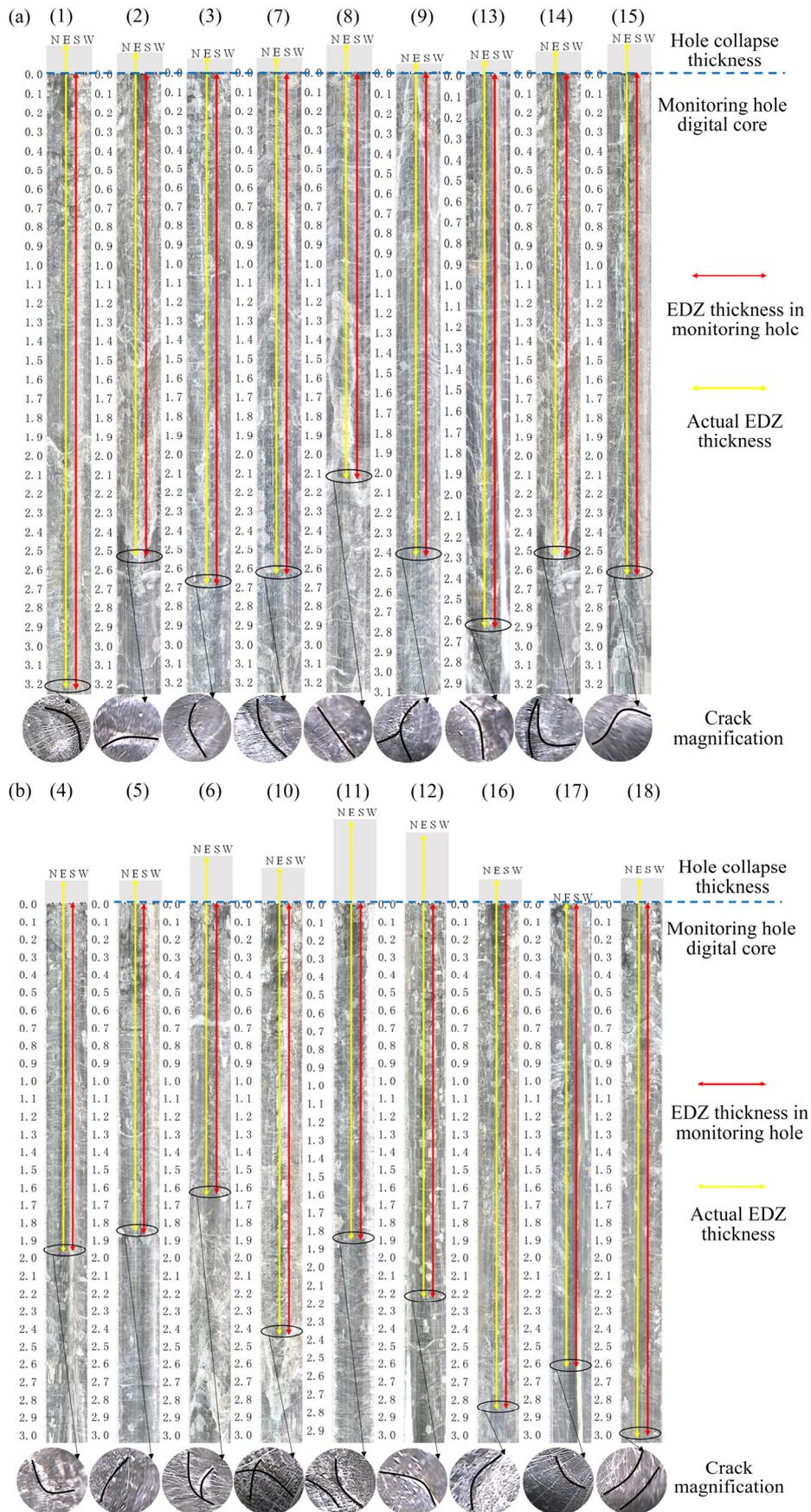**Fig. 5** Field monitoring equipment of EDZ

Fig. 6 Monitored hole digital core images, including digital core images of upper-level monitoring holes (a) and lower-level monitoring holes (b)

time, status of the high-frequency impact hammer and the excavator, pillar morphology, mining volume, peeling ore lumpiness, dust condition, roof condition, and wear condition of the bucket teeth of impact hammer tip. The daily excavation status is given in Table 4. The morphology changes of the pillar are shown in Fig. 7.

During the field application, the excavator operated for a total of 370 min, of which the effective excavation time was 341 min, and the

labor hours utilization rate was 0.92, which is much higher than that of the drilling and blasting method. Four excavation modes, namely cutting orebody floor, excavating stress relief slot, excavating pillar directly without excavating stress relief slot and excavating pillar after excavating stress relief slot, were used to take the ore pillar mining. The field operations of the above four excavation modes are shown in Fig. 8. Due to the different excavation modes, the daily excavation efficiency changes

Table 3 Monitoring results and distribution of EDZ

No.	EDZ thickness in monitoring hole, L_1/m	Hole collapse thickness, L_2/m	Actual EDZ thickness, L_3/m	Arrangement of monitoring holes
1	3.26	0.15	3.41	
2	2.56	0.10	2.66	
3	2.70	0.05	2.75	
7	2.65	0.07	2.72	
8	2.15	0.16	2.31	
9	2.33	0.02	2.35	
13	2.40	0.05	2.45	
14	2.70	0.06	2.76	
15	2.65	0.13	2.78	
4	1.99	0.12	2.11	
5	2.10	0.13	2.23	
6	1.66	0.26	1.92	
10	2.44	0.18	2.62	
11	1.85	0.47	2.32	
12	2.22	0.39	2.61	
16	2.67	0.12	2.79	
17	2.68	0.00	2.68	
18	3.03	0.13	3.16	

Table 4 Daily excavation status

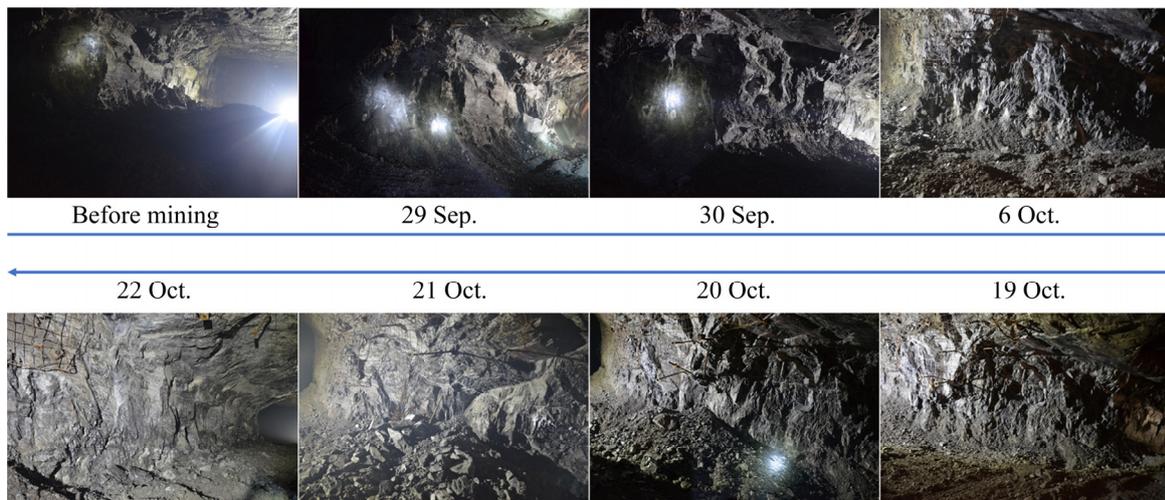| Date	Daily operation time/min	Daily excavation time/min	Daily mined ore volume/t	Excavation efficiency/(t·h⁻¹)	Utilization rate of labor hours
29 Sep.	115	98	90.2	55.2	0.85
30 Sep.	48	40	22.6	33.9	0.83
6 Oct.	32	32	16.0	30.0	1.00
19 Oct.	44	44	16.8	22.9	1.00
20 Oct.	28	24	7.3	18.3	0.86
21 Oct.	42	42	66.7	95.3	1.00
22 Oct.	61	61	68.2	67.1	1.00
Accumulated	370	341	287.8	50.6	0.92

Fig. 7 Morphology changes of pillar

Fig. 8 Field excavation operation, including four excavation modes of excavating pillar directly without excavating stress relief slot (a), cutting orebody floor (b), excavating stress relief slot (c), and excavating pillar after excavating stress relief slot (d)

significantly. Therefore, in order to show excavation efficiency under different excavation modes more intuitively, the statistics of the excavation performance of different excavation modes are given in Table 5. In field application, the overall excavation efficiency can reach 50.6 t/h, which proves the feasibility of the application of non-blasting mechanized mining using a high-frequency impact hammer in deep hard rock. Among the four excavation modes, the excavation efficiencies in orebody floor and stress relief slot are lower than the overall excavation efficiency. The efficiency of pillar excavation without excavating stress relief slot is basically the same as the overall efficiency, while the efficiency of pillar excavation after excavating stress relief slot is much higher than the overall efficiency, reaching 158.2 t/h.

Table 5 Excavation performances of different excavation modes

Excavation mode	Time/ min	Mined ore/t	Efficiency/ (t·h^{-1})
Excavating pillar directly without excavating stress relief slot	130	107.4	49.6
Cutting orebody floor	40	21.2	31.8
Excavating stress relief slot	138	72.2	31.4
Excavating pillar after excavating stress relief slot	33	87	158.2
Overall	341	287.8	50.6

The average area of a single peeling ore is obtained by counting the number of ore blocks in a unit area, and the equivalent diameter of a single peeling ore was calculated as the peeling ore lumpiness. The peeling ore is shown in Fig. 9, and the records of daily peeling ore lumpiness are given in Table 6. The peeling ore lumpiness is generally about 0.078 m, which does not require secondary crushing and meets the standard of direct ore mining.
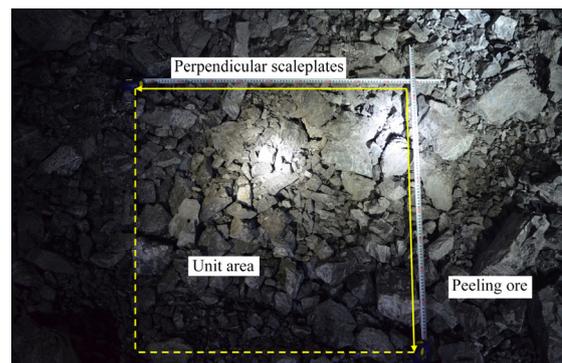

Fig. 9 Peeling ore

Table 6 Records of daily peeling ore lumpiness

Date	Ore lumpiness/m
29 Sep.	0.0086
30 Sep.	0.0075
6 Oct.	0.0075
19 Oct.	0.0076
20 Oct.	0.0072
21 Oct.	0.007
22 Oct.	0.0095

In the field application, the dust is less. Compared with the drilling and blasting method, no toxic gas such as blasting smoke was generated, which ensures the safety and health of the operators. However, during excavation of the hard ore rock in the non-EDZ area or stress relief slot, it is difficult to break ore rock, and the bucket teeth was required to exert high-frequency impact, resulting in the increased and heavy friction between ore rock and bucket teeth and the relatively large dust. Although the dust condition was relatively severe, as shown in Fig. 10, it can be seen that it was still significantly better than that of the drilling and blasting method.
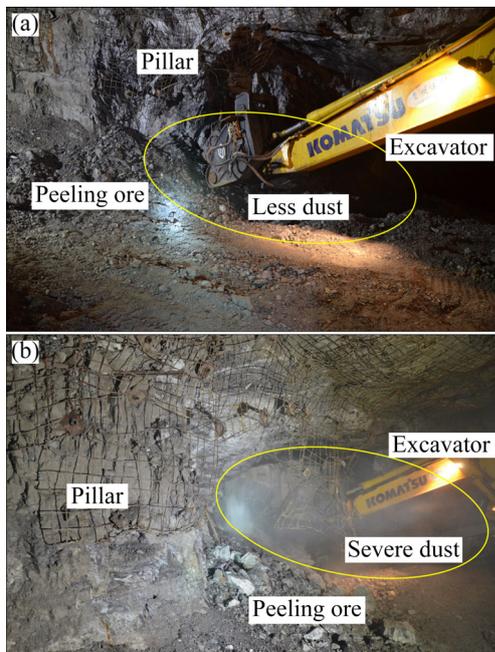

Fig. 10 Dust condition, including less dust condition (a) and severe dust condition (b)

In the field application, the roof is stable, indicating that non-blasting mechanized mining has

the advantage of less disturbance and improving the safety of mining. When the exposed area of the roof is large, the combined anchor net and anchor cable were used to support the roof, as shown in Fig. 11.
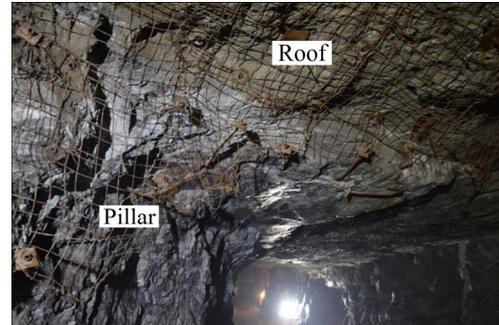
Fig. 11 Roof condition

In the process of interaction between bucket teeth and ore rock, the tip of bucket teeth was affected by high contact stress and high temperature, and it would be worn and even easily truncated, which greatly affected the excavation efficiency. During the field application, the bucket teeth were truncated once, and two bucket teeth were consumed accumulatively. The normal wear and truncation situations of bucket teeth are shown in Fig. 12. Because it was difficult to excavate the stress relief slot, the wear and truncation of the bucket teeth mainly occurred in this stage, while the
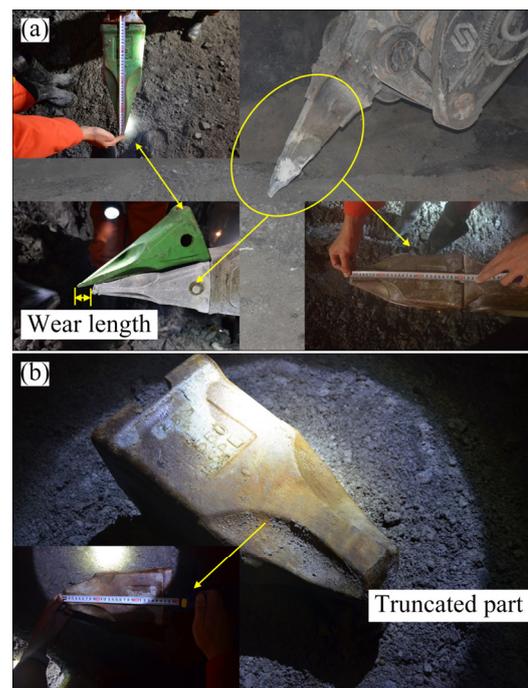
Fig. 12 Field situations of bucket teeth, including normal wear (a) and truncation (b)

consumption of the bucket teeth was less when the pillar was excavated after excavating stress relief slot.

5 Discussion

5.1 Influence of rock defects on rock cuttability

Rock cuttability is determined by rock properties, which can reflect the difficulty of rock breakage in mining. In the experiments carried out on the ore rock, the parameters of PCF and SE can directly reflect the rock cuttability. Lower PCF and SE represent higher rock cuttability. The results of four times of rock breakages have great differences, which are caused by the defects in the rock sample, including boreholes and fissures. The comparison of defects in the rock sample from the four tests is given in Table 7.

Table 7 Comparison of defects in rock sample from four tests

Defects in rock sample	PCF/kN	SE/(J·cm^{-3})
Intact rock sample	28.31	0.0653
Boreholes, far from surface	28.68	0.0070
Boreholes, close to surface	12.36	0.0068
Fissures	10.59	0.0018

Through comparison, it can be found that the rock defects such as boreholes and fissures can improve the rock cuttability and rock breaking efficiency in the varying degrees. The borehole, as a free surface inside the rock sample, is conducive to the development of cracks and the formation of fracture surfaces, and can greatly reduce the energy required for rock breakage. As a result, the SE of the drilled rock sample is much lower than that of the intact rock sample. Since boreholes affect rock breakage by adding new free surfaces, the location of boreholes has a non-negligible effect on rock breakage. When the borehole is closer to the cutter working point, the PCF required for rock breakage is significantly reduced. When subjected to pick force, the fissures in the rock sample propagate and develop, and a small pick force can cause the fissures to develop through the free surface and make the rock sample completely split. The pick force required to make the fissures contained in the rock sample go through the free surface is smaller, which results in lower PCF and SE required for

failure of the rock sample with fissures than those of the rock sample with boreholes.

The defects such as boreholes and fissures can affect the rock cuttability and change the failure mode to some extent. In deep hard rock mining, especially for ore bodies that are difficult to be excavated, the rock cuttability can be improved by means of artificial pre-fracture and pre-drilling. By artificial pretreatment, the mechanical excavation tools can easily invade the ore body and improve the excavation efficiency. Therefore, in further studies, it is necessary to explore how defects can be used to more efficiently improve rock cuttability and induce fracture surfaces to be formed according to excavation requirements.

5.2 Effective use of EDZ and stress relief slot

The triaxial stress condition of in-situ ore body is gradually changed to biaxial stress condition and uniaxial stress condition by excavating preparation and cutting entryways for forming a peninsula-type pillar. The release of horizontal stress will cause stress concentration in the vertical direction. The stress redistribution leads to the development of cracks, thus forming the EDZ. In traditional mining, the development of cracks caused by blasting will affect the stability of roof, and a large number of supporting operations are needed to ensure the safety of mining operations, which greatly hinders the mining process and efficiency. Different from drilling and blasting method, non-blasting mechanized mining requires the safe and efficient utilization of EDZ because of the high rock cuttability in the EDZ affected by the crack defects in the ore body. The efficient utilization of EDZ can be realized by expanding the scope of EDZ and changing the mining mode in EDZ.

According to the field monitoring of EDZ, the thickness of the EDZ is 1.92−3.41 m. The distribution of the EDZ thickness on each free surface presents a characteristic that the two sides are higher than the middle, which indicates that the stress redistribution caused by the change from triaxial stress to uniaxial stress has a greater influence on the development of cracks than that from triaxial stress to biaxial stress. Therefore, the range of the EDZ can be expanded by changing the stress condition of orebody through entryways excavation. Furthermore, according to the field monitoring result, the high-frequency impact during

mechanical excavation made the cracks continue to extend, resulting in the expansion of the EDZ range. In terms of the current research status and the development of mining equipment, we suggest that the non-blasting mechanized mining of hard rock mines should be designed and adjusted according to the EDZ range. When the ore body is mined within the EDZ range, the high in-situ stress on the pillar will undergo stress transfer and stress redistribution, so that the fractures in the pillar will develop inwards to form a new EDZ. In other words, after the mining of the ore body within the EDZ range of the pillar is completed, the equipment is transferred to mine the adjacent pillar. After a period of time, the pillar will form a secondary EDZ. Through various monitoring equipment, the static EDZ range data can be obtained, but there is still a lack of relevant research on the changing law of EDZ range and the secondary formation law. In further research, we will carry out dynamic monitoring experiments on EDZ to clarify the law of change and secondary formation of EDZ, and provide data and theoretical support for more efficient use of EDZ.

In order to further release the stress in the vertical direction, the stress relief slot was excavated at the bottom of the pillar. The ore body above the stress relief slot changes from the uniaxial confining stress condition to the non-confining stress condition, which had been proven to be beneficial to improving rock cuttability. In this field application, the efficiency of pillar excavation after excavating stress relief slot was increased by two times compared with the overall excavation efficiency. While releasing the stress, the stress relief slot creates a new free surface and compensation space for rock breakage. After losing the support of the bottom ore body, the part of the fractured ore body above the stress relief slot will collapse naturally. The excavation of stress relief slot can effectively improve the efficiency of non-blasting mechanized mining, but how to improve the excavation efficiency of stress relief slot is an urgent problem to be solved in the future.

5.3 Advantages and disadvantages of non-blasting mechanized mining using high-frequency impact hammer

The high-frequency impact hammer breaks the rock through "static load + high-frequency vibration", which can be regarded as the combination of dynamic and static rock breakage, which has a satisfactory ability for hard rock fragmentation. Compared with the traditional piston impact hammer, the high-frequency impact hammer driven by the hydraulic motor has a lower single strike force, but with up to 1500 vibration shocks per minute, and its total work is 3−5 times higher than that of the piston impact hammer. Compared with the roadheader, the high-frequency impact hammer has a smaller working area and can exert a higher destructive force on the rock mass, which is conducive to breaking the hard rock.

In the field application, we found that the non-blasting mechanized mining using high-frequency impact hammer has the advantages of small lumpiness of spalling ore, little dust, little excavation damage and high excavation efficiency, which can meet the requirements of safe and high-efficient mining. In the EDZ, the cracks develop well. The cracks produced by the high-frequency impact of the bucket teeth on the working face are expanded and can be connected to different cracks, which is conducive to the fall of ore rocks. The high-frequency vibration applied by the high-frequency impact hammer to the ore body can not only promote the collapse of the ore, but also promote the development of cracks and expand the scope of the EDZ.

However, in the field application, the disadvantages of the application of high-frequency impact hammer in hard rock mining is also exposed. On the one hand, the small working area of the high-frequency impact hammer affects the excavation efficiency. On the other hand, in the process of rock breakage, the force required for rock breakage is provided by controlling the forward movement of the excavator, which leads to the tilt of excavator body under the support of the cantilever when the ore body is difficult to be excavated. In order to solve the above-mentioned problems, the improvement measures for the high-frequency impact hammer are proposed. The first is to increase the number of bucket teeth to expand the working area. The second is to change the power application device of the high-frequency impact hammer, so that itself can apply the static load and high-frequency vibration to the bucket teeth. This method can make the high-frequency impact hammer press the bucket teeth against the ore body and then apply high-frequency vibration to

avoid empty hitting. In addition, the cooling device that can spray water mist to the bucket teeth and working face can be added to cool the severe friction bucket teeth to reduce the high temperature, teeth consumption and working face dust.

5.4 Methods for improving non-blasting mechanized mining efficiency

At present, many field tests of non-blasting mechanized mining in hard rock mines have proven that the use of non-blasting mechanized mining in hard rock mines instead of drilling and blasting method has a bright future. However, these field tests also reflect that the application of different equipment in hard rock mines still has many shortcomings in various aspects. Therefore, it is necessary to propose a non-blasting mechanized mining method based on the existing rock breakage equipment. Based on the field application in this study, the following non-blasting mechanized mining method is proposed.

In the preparation stage of mining stope, the preparation entryway and the cutting entryways perpendicular to the preparation entryway are excavated to form a peninsular-type pillar. Under the action of stress redistribution, the fissures in ore-rock develop around the entryways, forming EDZ that is easy to be excavated. By increasing the number of cutting entryways, the EDZ range can be expanded, and the proportion of the easily excavated area in the ore body can be increased. Then, the surface near the side of the preparation entryway can be taken as the working surface, and a roadheader can be used to excavate a stress relief slot at the bottom. Through the above constructions,

the ore body to be mined has realized the change from the stress condition of triaxial confining stress to the low uniaxial confining stress or even no confining stress, which has been proven to improve the rock cuttability. Compared with the bottom−up reciprocating mining, the left−right reciprocating mining can make better use of the characteristics of the ore body above the stress relief slot that has no confining stress and is prone to naturally collapse. Therefore, the ore body above the stress relief slot is divided into a plurality of long strip ore bodies in the left and right directions. Using the improved high-frequency impact hammer can break the ore rock on each long-strip ore body in a fixed direction. The operation starts from the long-strip ore body at the lowest side and gradually advances upward until the mining of ore body above the stress relief slot is completed. The working surface is pushed forward to continue the excavation of the stress relief slot and the left−right reciprocating mining of the ore body above the stress relief slot. This cycle continues until the mining of ore body within the EDZ range is completed.

On the one hand, the above mining method changes the stress condition of ore rock to make it under no confining stress as far as possible to improve the rock cuttability. On the other hand, it improves the existing high-frequency impact hammer and makes it more suitable for hard rock mining. In addition, for extremely hard ore bodies, artificial rock defects such as pre-fracturing and pre-drilling are required to assist rock breakage. The overall idea for improving the efficiency of non-blasting mechanized mining is shown in Fig. 13.
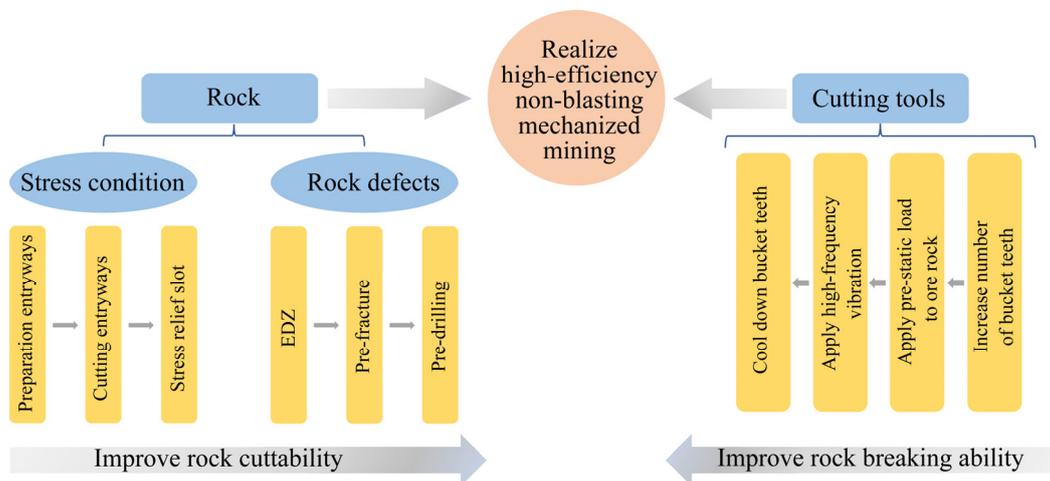

Fig. 13 Overall idea for improving efficiency of non-blasting mechanized mining

6 Conclusions

(1) According to the field monitoring of EDZ using high-definition drilling television, it is determined that the thickness of EDZ is 1.92−3.41 m. At present, non-blasting mechanized mining in hard rock mines should focus on mining ore bodies within the EDZ range.

(2) A large-size ore sample was obtained from the ore body, and a rock breaking experiment using a point-attack pick was carried out. The PCF of 28.31 kN can completely split the ore sample with the SE of 0.0653 J/cm^3. By exploring the influence of defects such as boreholes and fissures in ore sample on PCF and SE required for rock breaking, it can be found that rock defects can improve the rock cuttability in different degrees.

(3) The overall excavation efficiency and the excavation efficiencies in stress relief slot and in pillar after excavating stress relief slot are 50.6, 31.4 and 158.2 t/h, respectively. It is shown that the application of high-frequency impact hammer in hard rock has good feasibility, but it is difficult to excavate stress relief slot. In the mining process, non-blasting mechanized mining using high-frequency impact hammer exhibits the advantages of high efficiency, high utilization rate of working hours, small lumpiness of spalling ore, little dust, and little excavation disturbance. To realize high-efficiency non-blasting mechanized mining, it is necessary to improve the rock cuttability and improve the rock breaking ability of the cutting tools.

Acknowledgments

References

[1] LI Xi-bing, GONG Feng-qiang, TAO Ming, DONG Long-jun, DU Kun, MA Chun-de, ZHOU Zi-long, YIN Tu-bing. Failure mechanism and coupled static−dynamic loading theory in deep hard rock mining: A review [J]. Journal of Rock Mechanics and Geotechnical Engineering, 2017, 9(4): 767−782.

[2] WANG Shao-feng, LI Xi-bing, WANG Shan-yong, LI Qi-yue, CHEN Chong, FENG Fan, CHEN Ying. Three-dimensional orebody modelling and intellectualized longwall mining for stratiform bauxite deposits [J]. Transactions of Nonferrous Metals Society of China, 2016, 26: 2724−2730.

[3] WANG Shao-feng, LI Xi-bing, WANG Shan-yong. Three-dimensional mineral grade distribution modelling and longwall mining of an underground bauxite seam [J]. International Journal of Rock Mechanics and Mining Sciences, 2018, 103: 123−136.

[4] WANG Shao-feng, LI Xi-bing, YAO Jin-rui, GONG Feng-qiang, LI Xiang, DU Kun, TAO Ming, HUANG Lin-qi, DU Shao-lun. Experimental investigation of rock breakage by a conical pick and its application to non-explosive mechanized mining in deep hard rock [J]. International Journal of Rock Mechanics and Mining Sciences, 2019, 122: 104063.

[5] BILGIN N, COPUR H, BALCI C. Mechanical excavation in mining and civil industries [M]. Boca Raton: CRC Press, Taylor and Francis Group, 2013.

[6] HOOD M. Cutting strong rock with a drag bit assisted by high-pressure water jets [J]. Journal of the Southern African Institute of Mining and Metallurgy, 1976, 77(4): 79−90.

[7] COOK N G W, JOUGIN N C, WIEBOLS G A. Rock-cutting and its potentialities as a new method of mining [J]. Journal of the Southern African Institute of Mining and Metallurgy, 1968, 68(10): 435−454.

[8] OCAK I, BILGIN N. Comparative studies on the performance of a roadheader, impact hammer and drilling and blasting method in the excavation of metro station tunnels in Istanbu [J]. Tunnelling and Underground Space Technology, 2010, 25(2): 181−187.

[9] WANG Shao-feng, TANG Yu, LI Xi-bing, DU Kun. Analyses and predictions of rock cuttabilities under different confining stresses and rock properties based on rock indentation tests by conical pick [J]. Transactions of Nonferrous Metals Society of China, 2021, 31(6): 1766−1783.

[10] MA Hong-su, GONG Qiu-ming, WANG Ju, YIN Li-jun, ZHAO Xiao-bao. Study on the influence of confining stress on TBM performance in granite rock by linear cutting test [J]. Tunnelling and Underground Space Technology, 2016, 57: 145−150.

[11] KANG H, CHO J W, PARK J Y, JANG J S, KIM J H, KIM K W, ROSTAMI J, LEE J W. A new linear cutting machine for assessing the rock cutting performance of a pick cutter [J]. International Journal of Rock Mechanics and Mining Sciences, 2016, 88: 129−136.

[12] BILGIN N. Investigation into the mechanical cutting characteristics of some medium and high strength rocks [D]. University of Newcastle, Upon Tyne, 1977.

[13] ZHANG Z X, WANG S F, HUANG X, KWOK C Y. TBM–block interaction during TBM tunneling in rock masses: block classification and identification [J]. International Journal of Geomechanics, 2017, 17(5): E4016001.

[14] LI Xi-bing, WANG Shao-feng, WANG Shan-yong. Experimental investigation of the influence of confining stress on hard rock fragmentation using a conical pick [J]. Rock Mechanics and Rock Engineering, 2018, 51(1): 255−277.

[15] WANG Shao-feng, SUN Li-cheng, LI Xi-bing, WANG Shan-yong, DU Kun, LI Xiang, FENG Fan. Experimental investigation of cuttability improvement for hard rock

fragmentation using conical cutter [J]. International Journal of Geomechanics, 2020, 21(2): 06020039.

[16] WANG Shao-feng, TANG Yu, WANG Shan-yong. Influence of brittleness and confining stress on rockcuttability based on rock indentation tests [J]. Journal of Central South University, 2021, 28(9): 2786−2800.

[17] COPUR H, OZDEMIR L, ROSTAMI J I. Roadheader applications in mining and tunneling [J]. Mining Engineering. 1998, 50(3): 38−42.

[18] ERGIN H, ACAROGLU O. The effect of machine design parameters on the stability of a roadheader [J]. Tunnelling and Underground Space Technology, 2007, 22(1): 80−89.

[19] YANG Dao-long, LI Jian-ping, WANG Li-ping, GAO Kui-dong, TANG You-hong, WANG Yan-xiang. Experimental and theoretical design for decreasing wear in conical picks in rotation-drilling cutting process [J]. International Journal of Advanced Manufacturing Technology, 2015, 77(9−12): 1571−1579.

[20] DEWANGAN S, CHATTOPADHYAYA S. Characterization of wear mechanisms in distorted conical picks after coal cutting [J]. Rock Mechanics and Rock Engineering, 2016, 49(1): 225−242.

[21] CAI Xin, ZHOU Zi-long, DU Xue-ming. Water-induced variations in dynamic behavior and failure characteristics of sandstone subjected to simulated geo-stress [J]. International Journal of Rock Mechanics and Mining Sciences, 2020, 130: 104339.

[22] LI Shao-jun, FENG Xia-ting, LI Zhan-hai, ZHANG Chuan-qing, CHEN Bing-rui. Evolution of fractures in the excavation damaged zone of a deeply buried tunnel during TBM construction [J]. International Journal of Rock Mechanics and Mining Sciences, 2012, 55: 125−138.

[23] SONG Heng-yu, SHI Huai-zhong, JI Zhao-sheng, WU Xiao-guang, LI Gen-sheng, ZHAO He-qian, WANG Gao-sheng, LIU Yong, HOU Xin-xu. The percussive process and energy transfer efficiency of percussive drilling with consideration of rock damage [J]. International Journal of Rock Mechanics and Mining Sciences, 2019, 119: 1−12.

[24] BILGIN N, DEMIRCIN M A, COPUR H, BALCI C, TUNCDEMIR H, AKCIN N. Dominant rock properties

affecting the performance of conical cutters and the comparison of some experimental and theoretical results [J]. International Journal of Rock Mechanics and Mining Sciences, 2006, 43(1): 139−156.

[25] WANG Shao-feng, LI Xi-bing, DU Kun, WANG Shan-yong. Experimental investigation of hard rock fragmentation using a conical pick on true triaxial test apparatus [J]. Tunnelling and Underground Space Technology, 2018, 79: 210−223.

[26] WANG Shao-feng, LI Xi-bing, DU Kun, WANG Shan-yong, TAO Ming. Experimental study of the triaxial strength properties of hollow cylindrical granite specimens under coupled external and internal confining stresses [J]. Rock Mechanics and Rock Engineering, 2018, 51(7): 2015−2031.

[27] XU X L, KARAKUS M. A coupled thermo-mechanical damage model for granite [J]. International Journal of Rock Mechanics and Mining Sciences, 2018, 103: 195−204.

[28] LI Xi-bing, ZHOU Jian, WANG Shao-feng, LIU Bing. Review and practice of deep mining for solid mineral resources [J]. The Chinese Journal of Nonferrous Metals, 2017, 27(6): 1236−1262 (in Chinese).

[29] WANG Shao-feng, HUANG Lin-qi, LI Xi-bing. Analysis of rockburst triggered by hard rock fragmentation using a conical pick under high uniaxial stress [J]. Tunnelling and Underground Space Technology, 2020, 96: 103195.

[30] WANG Shao-feng, SUN Li-cheng, HUANG Lin-qi, LI Xi-bing, SHI Ying, YAO Jin-rui, DU Shao-lun. Non-explosive mining and waste utilization for achieving green mining in underground hard rock mine in China [J]. Transactions of Nonferrous Metals Society of China, 2019, 29: 1914−1928.

[31] LI Xi-bing, GU De-sheng. The hazard control and cataclastic mutagenesis induced by high stress in hard rock mining at depth [C]//The 175th Xiangshan Science Congress. Beijing: China Environmental Science Press, 2002: 101−108 (in Chinese).

[32] LI Xi-bing, YAO Jin-rui, DU Kun. Preliminary study for induced fracture and non-explosive continuous mining in high-geostress hard rock mine—A case study of Kaiyang phosphate mine [J]. Chinese Journal of Rock Mechanics and Engineering, 2013, 32(6): 1101−1111 (in Chinese).

深部硬岩矿山高频冲击锤非爆机械化开采现场应用

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摘 要：采用高频冲击锤开展非爆机械化开采现场试验，研究高频冲击锤在深部硬岩矿山应用的可行性。现场开采试验前，先监测矿体上开挖松动区范围，并从待开采矿柱上取样，进行截齿破岩试验，指导现场采矿试验。采矿试验中高频冲击锤的整体开采效率达到 50.6 t/h，开挖卸压槽后开采其上部矿体效率高达 158.2 t/h。这表明高频冲击锤在深部硬岩矿山具有良好的应用前景，卸压槽有利于非爆破机械化开采。同时，高频冲击锤还表现出工时利用率高、剥落矿块块度小、粉尘少、开采扰动小等优点。最后，基于现场应用和截齿破岩试验结果，提出基于高频冲击锤的深部硬岩矿山非爆机械化开采方法。

关键词：硬岩矿山；非爆机械化开采；高频冲击锤；开挖松动区；卸压槽；采矿方法

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