Research Article

Exploration and Practice of Pressure Relief by Slotting Coal Seams with a Diamond Wire Saw

Zhu Tang ^{1,2,3} Shuqing Li ^{1,2} Fei Huang ^{1,2} Shouqing Huang^{1,4} and Kangxu Cai^{1,2}

¹Hunan Provincial Key Laboratory of Safe Mining Techniques of Coal Mines,
Work Safety Key Laboratory on Prevention and Control of Gas and Roof Disasters for Southern Coal Mines,
Hunan University of Science and Technology, Xiangtan 411201, Hunan, China

²School of Resource Environment and Safety Engineering, Hunan University of Science and Technology, Xiangtan 411201,
Hunan, China

³School of Mines and Civil Engineering, Liupanshui Normal University, Liupanshui 553004, Guizhou, China

⁴Guizhou Pan Jiang Coal and Electricity Refco Group Ltd., Guiyang 550081, Guizhou, China

Correspondence should be addressed to Shuqing Li; 2793997437@qq.com

Received 20 March 2021; Accepted 6 May 2021; Published 13 May 2021

Academic Editor: Xianjie Hao

Copyright © 2021 Zhu Tang et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

To safely and economically eliminate the threat of high geostress in the coal mining process, based on the engineering case study of pressure relief by slotting residual coal pillars at a mine in the Kailuan mining area, a method of pressure relief by slotting coal seams with a wire saw was explored, and numerical simulation was carried out. The results show that the wire saw can cut coal seams in a large area, with a cutting efficiency and slotting depth greater than those of hydraulic slotting; a stress concentration zone forms in front of the wire saw coal cutting working face and a stress reduction zone and a stress recovery zone form behind. The pressure relief range varies, increasing at first and then decreasing. The exploration and practice of pressure relief by slotting coal seams with a diamond wire provides theoretical guidance and practical reference for pressure relief by slotting coal seams.

1. Introduction

High geostress during coal mining is a great threat to coal mine production safety, and slotting pressure relief is an effective method to release high geostress in coal seams [1–4]. Based on the principle of water hammer pressure breaking coal by high-pressure water jet impact, high-pressure water jet seam slotting equipment and technology have been developed and applied under certain conditions [5–7]. The high-pressure water jet pressure in use is 60~100 MPa, and the diameter of the nozzle is 2~2.5 mm. When coal rocks with a firmness coefficient f of 0.3~1 are cut under these conditions, an annular slot with the slot height of 2~6 cm and the slot depth of 1.5~2.5 m can be obtained [8]. In practice, due to the limited influence range of hydraulic slotting, to realize large-area pressure relief by slotting coal seams, it is often necessary to drill multiple boreholes and cut multiple intermittent slots in the coal seams to carry out joint pressure relief, which requires a

great deal of manpower and is very costly. To find a safe and economical method for large-area coal seam slotting, a diamond wire saw (DWS) is used to replace the high-pressure water jet to cut coal seams for pressure relief. In this paper, a method of slotting coal seams with a wire saw is proposed. Through numerical simulation and the practice of pressure relief by cutting coal pillars with a wire saw, the changes in the vertical stress of coal rocks and the range of pressure relief during the advancing process of the working face with wire saw coal cutting are studied, aiming to provide theoretical guidance for pressure relief by slotting coal seams with a wire saw.

2. Engineering Practice of Coal Seam Slotting

2.1. Proposed Slotting Coal Seams with a DWS Method for Pressure Relief. When a mine in the Kailuan mining area was in the deep mining stage, under the influence of high geostress and remnant pillar, the coal rock impact dynamic

instability was severe. A total of 47 dynamic failures were documented above the mining depth of -530 m, and the other dynamic failures occurred in the normal mining working face below the mining depth of -630 m. At this mine, the false roof of the residual coal pillars consisted of dark gray mudstone. The immediate roof consisted of relatively hard laminated gray siltstone and medium-grained sandstone. The direct floor was composed of hard sandy mudstone and siltstone. The hard floor was composed of fine- and medium-grained sandstone, which was hard and relatively brittle. On this basis, to explore a safe and economical method for relieve the pressure of the residual coal pillars and reduce and eliminate the threat of high geostress, the Hunan University of Science and Technology and Kailuan Group jointly developed a set of equipment for slotting coal seams with a wire saw and carried out a pressure relief by cutting coal pillars with a single wire between the T3150 air channel and T2051 North driving roadway No. 2.

2.2. Effect and Process of Slotting Coal Seams with a Wire Saw.

Wire saw cutting is an advanced cutting method that is simple to perform and has a high flexibility [9–12]. The principle of slotting coal seams with wire saw is as follows. The wire saw machine drives the diamond beaded rope to move at high speed in the coal seam. The diamond particles on the wire saw continuously grind the coal body. The wire saw machine moves on the track to drive the beaded rope to feed, and the wire saw continuously cuts the coal seam inward. After slotting the coal seam, a narrow and long slot space similar to the goaf is formed inside the coal seam. It is generally believed that Hertz fracture and volume break are the main ways of diamond particles cutting fractured rock mass [13–15].

A slotting system with a wire saw generally consists of a wire saw machine, a guide device, a string bead wire, and a control and auxiliary system. A working face can be constructed by cutting drilling and wire return drilling in the coal seam, as shown in Figure 1. The preparation work before slotting mainly includes equipment installation, wire winding, and reeving. There are three steps for operation. Step 1: the first group guide device is installed in one side of the roadway, and the wire saw machine and the second group guide device are installed in the other side of the roadway. Step 2: the string bead wire is reeved through the borehole. The string bead wire is wound through the driving wheel, and the device of the wire saw machine is guided in turn. The tension of the string bead wire is adjusted. Then, the string bead wire with a joint is fastened. Step 3: the wire saw machine is started, and the rotational speed of the driving wheel is adjusted. Next, the auxiliary system is started to spray water to cool the string bead wire and suppress the dust. Finally, the advancing speed of the wire saw on the track is controlled to cut the coal seams along the advancing direction from the start of drilling. The operating parameters of coal seam wire saw slotting are shown in Table 1. Engineering practice shows that the wire saw can cut the coal seam in a large area, with the linear cutting speed reaching 15 m/s and the cutting efficiency reaching 80 m²/h.

After cutting the coal pillars with the wire saw, there is a long narrow slot space left with a seam height of 15 mm and a seam depth of 30 m. The statistics indicate that both the working efficiency and seam depth after coal seam slotting with a wire saw are better than those after hydraulic seam slotting. The following numerical simulation focuses on the variation in vertical stress and pressure relief range in the advance of the working face when cutting coal seams with a wire saw.

3. Numerical Simulation of Pressure Relief by Wire Saw Slotting

To ensure the accuracy of numerical simulation and the solving efficiency, considering the practice of coal seam wire saw slotting engineering, we used the ratio function of FLAC^{3D} and applied the domain decomposition method to form a three-dimensional model composed of dense, transitional and loose grid areas, with dimensions of $100\text{ m} \times 10\text{ m} \times 18\text{ m}$, $528,000$ grid cells, and $580,860$ grid points, as shown in Figure 2(a). The dense grid around the slot in the model is partially enlarged, as shown in Figure 2(b).

A Mohr–Coulomb constitutive model was adopted. A 10 MPa vertical stress was applied on the upper boundary. Rolling boundary conditions were adopted on the front and back boundary, left and right boundary, and lower boundary. The horizontal stresses of the front, back, left, and right of the model were considered hydrostatic pressures. Lying in the middle part of the coal seam, the wire saw coal slotting working face advanced by 0.8 m each time from the start slotting position along the coal seam direction. The rock mechanics properties of each layer are shown in Table 2.

3.1. Vertical Stress Distribution. The vertical stress distribution during the advancement of the wire saw coal slotting working face is shown in Figure 3. According to Figure 3, when the wire saw coal slotting working face advanced by 0.8 m, two stress concentration zones, A_1 and A_2 , were formed on the left and right coal walls of the slot, respectively, and the vertical stress of the coal pillars approximately 1 m above and below the slot was released.

When the working face advanced by 11.2 m, the vertical stress 7 m above and 9 m below the slot was released, the range of the stress reduction zone B was greatly extended, the vertical stress in the stress reduction zone was reduced to approximately 0 MPa, the stress release rate was up to 100% , the two stress concentration zones A_1 and A_2 formed, the vertical stress in the stress concentration zone was increased to approximately 30 MPa, and the stress concentration factor became three.

When it advanced by 22.4 m, the stress recovery zone C formed in the middle of the slot, the vertical stress in the stress recovery zone returned to approximately 6 MPa, and the original stress reduction zone was divided into B_1 and B_2 , which were close to the A_1 side of the stress concentration zone and the A_2 side of the stress concentration zone, respectively. When it advanced by 33.6 m, the range

FIGURE 1: Schematic diagram of the test system and site layout for cutting coal pillars with DWS. (a) Layout chart and (b) A-A' side view.

TABLE 1: Operating parameters of the cutting system with DWS.

Type	W	v	Φ	h	d
Parameter	37	15	11.5	15	0.8

W = power, KW; v = linear velocity, ms^{-1} ; Φ = diameter, mm; h = slot height, mm; d = advanced distance, m.

FIGURE 2: Continued.

FIGURE 2: The FLAC^{3D} numerical simulation model.

TABLE 2: Rock mechanics properties.

Type	H	γ	E	μ	c	t	φ
Fine sandstone	4	2560	8.83	0.27	5.8	3.5	38
Mudstone	4	2150	5.51	0.31	3.5	2.8	30
Coal	2	1400	3.28	0.26	1.8	0.8	24
Mudstone	4	2150	5.51	0.31	3.5	2.8	30
Fine sandstone	4	2560	8.83	0.27	5.8	3.5	38

H = thickness, m; γ = unit weight, kgm^{-3} ; E = Young's modulus, GPa; μ = Poisson's ratio; c = cohesive forces, MPa; t = tensile strength, MPa; φ = angle of internal friction, $^\circ$.

FIGURE 3: Vertical stress distribution of different slot depths. (a) $L = 0.8$ m, (b) $L = 11.2$ m, (c) $L = 22.4$ m, and (d) $L = 33.6$ m.

FIGURE 4: L_{η}^s at different slot depths.

of the stress recovery zone C extended, the vertical stress in the stress recovery zone returned to approximately 8 MPa, and the changes in the stress of the stress concentration zone and the stress reduction zone on both sides were not obvious.

3.2. Vertical Stress Release and Stress Release Range. For the purpose of exploring the coal rock stress release and the changes in the pressure relief range, formula (1) presents the calculation method of the stress release rate. The FISH language in FLAC^{3D} software was used to analyze the 10%, 30%, 50%, 70%, and 90% vertical stress release at the top 0.7 m of the slot, as shown in Figure 4.

$$\eta = \frac{\sigma^i - \sigma^{i'}}{\sigma^i} \times 100\%, \quad (1)$$

where σ^i is the initial stress value of grid cells i , MPa; $\sigma^{i'}$ is the stress value of grid cells i after pressure relief, MPa; and η is the stress release ratio of grid cells i , %.

In Figure 4, the ordinate indicates the pressure release range L_{η}^s and the abscissa denotes the advancement distance of the wire saw coal slotting working face (slot depth). a, b, c, d, and e are the critical points at which the pressure relief range of the wire saw slotting changes from increasing to decreasing when the stress release rate is 10%, 30%, 50%, 70%, and 90%, respectively. Figure 4 shows that when $\eta = 10\%$, the wire saw coal slotting working face advances from 0.8 m to 23.2 m and L_{10}^s increases from 0.8 m to 22.2 m. When the working face advances from 23.2 m to 31.2 m, L_{10}^s is reduced from 22.2 m to 19 m. Thereafter, L_{10}^s does not change with increasing L .

When $\eta = 30\%$, the wire saw coal slotting coal working face increases from 0.8 m to 17.6 m, and L_{30}^s increases from 0.4 m to 16.8 m. When the working face advances from 17.6 m to 28 m, L_{30}^s is reduced from 16.8 m to 11.4 m. Thereafter, L_{10}^s does not change with increasing L .

At $\eta = 50\%$, the wire saw coal slotting working face advances from 0.8 m to 14.4 m, and L_{30}^s increases from 0.4 m to 16.8 m. When the working face advances from 14.4 m to 21.6 m, L_{30}^s is reduced from 13.4 m to 8 m. Thereafter, L_{10}^s does not change with increasing L .

When $\eta = 70\%$, the wire saw coal slotting working face advances from 0.8 m to 12 m and L_{30}^s increases from 0 m to 11.2 m. When the working face advances from 12 m to 25.6 m, L_{30}^s is reduced from 11.2 m to 6 m. Thereafter, L_{10}^s does not change with increasing L .

At $\eta = 90\%$, the wire saw coal slotting working face advances from 0.8 m to 10.4 m and L_{30}^s increases from 0 m to 9 m. When the working face advances from 10.4 m to 20 m, L_{30}^s is reduced from 9 m to 3.2 m. Thereafter, L_{10}^s does not change with increasing L .

During the advancement of the wire saw coal slotting working face, with the increase in L , L_{η}^s increases first and then reduces to a certain stable value. The relationship between L_{η}^s and L is fitted, as shown in Table 3.

4. Discussion

In the practice of slotting coal seams with wire saws, a 30 m slotting depth cut by a single wire has been realized. Under normal circumstances, the efficiency of coal seam wire saw slotting reaches 80 m²/h. Compared with those of the existing hydraulic slotting approaches, the depth and efficiency of coal seam wire saw cutting are approximately 5 times greater and equivalent, respectively. The advancing distance of wire saw slotting affects the pressure relief effect of wire saw slotting. When the working face advances from 0.8 m to approximately 10 m, the degree and range of pressure relief by slotting coal seams with a wire saw both increase significantly. After that, stress recovery occurs in the middle of the slot due to roof and floor contact, and the range of stress recovery increases with the continuous advancement of the working face, but the range of pressure

TABLE 3: Fitted formulas.

η (%)	Fitted formulas	R^2
10	$L_{10}^s = 1.106 \times 10^{-5} L^5 - 9.122 \times 10^{-4} L^4 + 0.025 L^3 - 0.286 L^2 + 2.197 L - 1.2814$	0.99
30	$L_{30}^s = 1.118 \times 10^{-8} L^8 - 1.472 \times 10^{-6} L^7 + 7.773 \times 10^{-5} L^6 - 0.0021 L^5 + 0.0308 L^4 - 0.2426 L^3 + 0.963 L^2 - 0.6585 L + 0.4716$	0.98
50	$L_{50}^s = -3.768 \times 10^{-9} L^8 + 6.453 \times 10^{-7} L^7 - 4.454 \times 10^{-5} L^6 + 0.0016 L^5 - 0.0313 L^4 + 0.3317 L^3 - 1.786 L^2 + 5.225 L - 3.509$	0.97
70	$L_{70}^s = -1.1707 \times 10^{-8} L^8 + 1.633 \times 10^{-6} L^7 - 9.2547 \times 10^{-5} L^6 + 0.0027 L^5 - 0.0439 L^4 + 0.3775 L^3 - 1.613 L^2 + 3.959 L - 2.44$	0.95
90	$L_{90}^s = -4.7243 \times 10^{-9} L^8 + 5.8536 \times 10^{-7} L^7 - 2.7663 \times 10^{-5} L^6 + 5.892 \times 10^{-4} L^5 - 0.0042 L^4 - 0.0356 L^3 + 0.5932 L^2 - 1.2196 L + 0.734$	0.91

η = vertical stress release ratio, %; L = slot depth, m.

relief by slotting coal seams with a wire saw decreases to a certain extent. This analysis shows that wire saw slotting is similar to mining a very thin “protective layer” in coal seams, delaying and controlling the roof and floor contact of the slot, which may allow the wire saw slotting to produce a better pressure relief effect than hydraulic slotting. In addition, in practice, when a high-pressure water jet is used to slot hard coal seams, the difficulty of cutting will be higher, and the slotting depth will be smaller. As the Mohs hardness of the objects cut by the wire saw is generally higher, wire saw slotting may have more advantages in slotting hard coal rocks, which may be more conducive to wire saw slotting operation and its pressure relief effect.

5. Conclusions

- (1) Wire saw slotting can cut a long and narrow slot in a coal seam, and its cutting efficiency and slotting depth are better than those of hydraulic slotting.
- (2) A stress concentration zone forms in front of the wire saw coal slotting working face, while the stress reduction zone and the stress recovery zone form behind the working face. In the advancing process of the wire saw coal slotting working face, the stress release range varies, increasing at first and then decreasing to a certain stable range with the increase in the advancing distance of the working face.
- (3) Partial stress recovery occurs after the roof and floor contact in the middle of the slot, which is the critical condition for the range of the pressure relief effect of wire saw slotting to change from increasing to decreasing. According to the actual situation, the creep and deformation characteristics of overlying coal rocks over the coal slot cut by a wire saw can be further explored.

Data Availability

All the data generated or published during the study are included within the article; no other data were used to support this study.

Conflicts of Interest

The authors declare that they have no conflicts of interest regarding the publication of this paper.

Acknowledgments

This study was funded by the National Natural Science Foundation of China (51974121 and 51804115), Open Research Fund Program of Hunan Province Key Laboratory of Safe Mining Techniques of Coal Mines (E21723), and Project of Liupanshui Science and Technology (52020-2018-03-06).

References

- [1] M. G. Qian and T. C. Liu, *Mine Pressure and its Control*, China University of Mining and Technology Press, Beijing, China, 1991.
- [2] L. M. Dou and X. Q. He, *Theory and Technology of Rock Burst Prevention*, China University of Mining and Technology Press, Xuzhou, China, 2001.
- [3] Y. S. Zhao, *Multi-field Coupling of Porous Media and its Engineering Response*, Science Press, Beijing, China, 2010.
- [4] A. Q. Lin, W. Yang, H. J. Wu et al., “A numeric analysis of the effects different factors have on slotted drilling,” *Journal of China University of Mining and Technology*, vol. 39, no. 2, pp. 153–157, 2010.
- [5] C. C. Li, “Application of high pressure hydraulic slotting in pressure relief and permeability enhancement of coal roadway,” *IOP Conference Series: Earth and Environmental Science*, vol. 526, no. 1, Article ID 012159, 2020.
- [6] B. Q. Lin, F. W. Meng, and H. B. Zhang, “Regional gas control based on drilling-slotting-extracting integration technology,” *Journal of China Coal Society*, vol. 36, no. 1, pp. 75–79, 2011.
- [7] F. Huang, Y. Y. Lu, X. C. Liu et al., “Breakage mechanism of transverse isotropic rock subjected to high-pressure water JET,” *Chinese Journal of Rock Mechanics and Engineering*, vol. 33, no. 7, pp. 1229–1335, 2014.
- [8] Y. J. Zhang and S. S. Guo, “Theoretical model of annular slotting depth for high pressure water jet and its application,” *Journal of China Coal Society*, vol. 44, no. 1, pp. 126–132, 2019.
- [9] Y. X. Lu, Y. Li, and H. Huang, “Study on sawing forces of diamond wire saw in concrete cutting,” *Diamond and Abrasives Engineering*, vol. 31, no. 6, pp. 47–50, 2011.
- [10] S. S. Rajpurohit, R. K. Sinha, P. Sen, and S. Singh, “Influence of physico mechanical properties of Indian dimension stones on cutting rate of diamond wire saw,” *Arabian Journal of Geosciences*, vol. 11, no. 18, 2018.
- [11] Z. Yang, “Structure and material properties of soft tissues,” *Finite Element Analysis for Biomedical Engineering Applications*, vol. 31, no. 2, pp. 45–48, 2019.
- [12] G. S. Huang, “Practice and application of wire saw cutting ore in underground mining of mirabilite mine in Qi Li well, Hengyang city, Hunan Province,” *Modern Chemical Research*, vol. 11, pp. 59–61, 2020.
- [13] F. C. Frank and B. R. Lawn, “On the theory of hertzian fracture,” *Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences*, vol. 299, no. 1458, pp. 291–306, 1967.
- [14] L. Baochang, Z. Zupei, S. Youhong et al., “Research into the sawing trajectory and mechanism of diamond wire saw,” *Diamond and Abrasives Engineering*, vol. 132, no. 4, pp. 17–21, 2002.
- [15] H. Guoqin, H. Hui, G. Hua et al., “Influences of sawing parameters on forces and energy in wire sawing of granite,” *Journal of Mechanical Engineering*, vol. 45, no. 3, pp. 234–239, 2009.