Research and Application of “Concentric Ring” Reinforcement and Sealing Technology for Gas Drainage Boreholes in Soft-Coal Seams

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ABSTRACT: The problems of lack of stability and difficult sealing of gas drainage boreholes in soft-coal seams directly affect the efficient extraction of gas in these soft-coal seams. After the holes are drilled, the collapsed holes lead to the failure to seal in time, which brings hidden dangers to mine production and causes time and economic waste. In this paper, the viscoelastic mechanics model is used to solve the force of the coal body in the fractured area of the orifice, combined with the theory of the external conditions affecting the collapse of the orifice of the soft-coal seam. The reason for the easy collapse of the borehole of the soft-coal seam is studied, and a reasonable solution is proposed. “Concentric ring” reinforced sealing technology, elaborated from the physical model, technical principles, and processes, was finally carried out in an on-site application test at the N2106 working face of a mining area in Shanxi. The results show that the fracture zone of the soft-coal seam easily enters a stage of rapid deformation under the effect of time. Its strong adsorption behavior, easy expansion, and other characteristics, combined with the violent disturbance of the drill pipe when the drilling is offset, eventually cause the hole to retreat, making it easy to deform and collapse afterward. The test boreholes reinforced and sealed with “concentric rings” have no problem of collapsed holes after retreating. The gas concentration remained above 30% in the first 30 days. The maximum gas purity of the borehole on the 30th day of extraction flow rate reached 0.053 m$^3$/min. It is found that the sealing effect of the “concentric ring” reinforced seal drilling technology is better than that of the traditional sealing technology.

1. INTRODUCTION

Gas drainage of coal seams can effectively improve mining efficiency and reduce production safety problems caused by a gas disaster. Gas control results show that gas predrainage can effectively eliminate the overlimit problem of gas concentration in the high gas mine roadway, and reduce and eliminate the risk of gas outburst in the mining face from the source. In China, there are many mines in soft-coal seams, and they are widely distributed. The low strength and poor stability of soft-coal seams make it difficult to seal holes for gas extraction in the soft-coal seams, which also directly leads to the effect of poor gas extraction in soft-coal seams.

The premise of coal seam gas extraction is drilling. Due to the characteristics of the soft-coal seam, under the interference of complex environments such as gas field, stress field, and mining disturbance, the borehole mouth area is prone to instability, deformation, and even hole collapse, as shown in Figure 1. In a soft-coal seam minefield, the survey found that a soft-coal seam drilled hole will frequently collapse causing the end of the drill hole to be collected under the tube seal. A drain hole cut again in terms of economics and time will cause great waste, and a hole that collapses after the orifice section of

a large number of air leakage passages also brings to the mine safety hidden trouble.

In recent years, a large number of domestic and foreign studies have focused on the instability of pumping boreholes and the reinforcement of sealing technology. Liang et al. established the mechanical model of borehole instability by carrying out mechanical theoretical analysis and analyzed the failure law of the coal body instability at the deep hole and hole wall. Wang et al. divided the drilling force into three areas and carried out a detailed theoretical mechanical modeling. Sun et al. proposed and developed the integrated technology concept of sealing and leakage disposal based on the traditional disposable bag sealing technology. Zhai et al. carried out a series of theoretical studies on the deformation and instability

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of drilling holes in soft-coal seams with high gas content and easy outburst and found that the rock strata stress and stress of the secondary distribution around the roadway are the essential reasons for these phenomena. Drilling reinforcement and sealing technology based on this is also reported frequently. Zhang et al. studied and obtained the relationship between the reinforcing borehole and the reduction of displacement around the hole, based on which he proposed and applied the "strong and weak" reinforcement dynamic sealing technology in the industry.

But, at present most studies of the instability of borehole sealing in the coal seam is in the qualitative research stage, and there is less research on the cause analysis of a drilling hole position collapse. Especially the reinforced sealing technology did not solve the problem of hole collapse. The process of drilling a hole causes gas extraction from the borehole seal, and deformation of the seal results in its failure. Finally, the sealing effect of gas extraction borehole in a soft-coal seam is still not ideal.

In this paper, based on the existing extraction from the borehole sealing section of stability study results, combined with the characteristics of the soft-coal seam and the theoretical analysis of soft-coal seam drilling hole area stress distribution of coal and collapse reason, the authors put forward a "concentric rings" reinforced sealing method, and expound in detail the method of the sealing process, finally testing the new reinforced sealing effect. The field application test was carried out on the N2106 belt routing working face of a mining area in Shanxi Province. The above research can provide a good theoretical basis for the reasonable improvement of the sealing of soft-coal seam gas extraction.

2. CAUSE ANALYSIS OF HOLE COLLAPSE OF THE BOREHOLE IN SOFT COAL SEAM

After the completion of roadway excavation, the original stress balance of the coal strata was broken, and the elastic-plastic failure deformation of the coal body was a result of the process of stress redistribution and balance. The stress concentration gradually transferred to the deep part of the coal body, and the stress reduction area, stress concentration area, and original stress area successively appeared from the surface surrounding rock of the roadway to the deep part. After drilling in the coal seam was completed, the length of the coal wall in the borehole was divided into the crushing zone, softening zone, and elastic-viscous zone from the direction of the borehole to the depth. The stress zones and stress conditions are shown in Figure 2.

2.1. Stress Environment Analysis of Borehole in Soft Coal Seam. Under the double damage of driving and drilling, the hole area is prone to collapse after the drilling of coal along the direction of the aperture stress is performed. Instantaneous deformation of the borehole occurs in the area of coal before and after the drilling process, and with time, the stress peak strength of coal undergoes an apparent strain softening effect. Drilling around the mechanics model of coal is as shown in Figure 3, The coal body around the pore can be divided into three zones: broken zone, softened zone, and elastic cohesive zone.

According to the mechanical model for solving the strength of softening zone under the time effect in literature, it can be obtained that the solution formula of tangential stress $\sigma_\theta^p$ and radial stress $\sigma_r^p$ for coal body in the mouth crushing zone is

$$\sigma_\theta^p = k_p \sigma_\theta^p + \sigma_\tau - \dot{\epsilon}_c A(t) \left( \frac{R_p}{r} \right)^2 - 1$$

(1)

Figure 1. Schematic diagram of on-site instability deformation of the borehole: (a) borehole collapse; (b) borehole deformation.

Figure 2. Schematic diagram of roadway-surrounding stress and borehole-around stress zones. I, stress lowering zone; II, postpeak stress rising zone; III, prepeak stress lowering zone; IV, primary stress zone.

Figure 3. The coal body around the borehole area stress and borehole-around stress zones.
Figure 3. Zoning map of coal body force in the orifice area. I, sealing material; II, crushing zone; III, softening zone; IV, elastic viscous zone.

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\sigma^p = \frac{2}{k_p + 1} \left( \frac{r}{R_p} \right)^{k_p-1} \left( \sigma_0 + \frac{A(t)t + \sigma}{k_p + 1} \right) + jA(t) \left( \frac{1}{k_p + 1} \left( \frac{R_p}{r} \right)^2 - \frac{1}{k_p - 1} \right) - \frac{\sigma}{k_p - 1} \tag{2}
\]

where \( \sigma_c \) is the uniaxial compressive strength of the coal body, MPa; \( j \) is softening coefficient, \( A(t) \) is the time effect equation, \( R_p \) is plastic zone radius, m; \( r \) is the distance from the center of the drilling hole, m; and \( k_p \) is the coefficient.

Since \( A(t) \) is an equation containing time variables and is positively correlated with time, it can be obtained from the above equation that the tangential stress and radial stress in the orifice crushing zone decrease with time. As the soft-coal seam itself has the characteristics of strong rheology and low strength, the coal body in the hole mouth broken area soon enters the stage of accelerated deformation after drilling, and the instability and collapse of the borehole will be the result of failing to seal off the borehole in a very short time, as shown in Figure 4.

2.2. Analysis of the Influence of External Environment on Borehole in Soft Coal Seam. The drilling in a soft-coal seam is easily affected by the external environment,\(^{23,24}\) which also aggravates the occurrence of hole collapse at the hole mouth to a certain extent. Specific analysis is as follows:

(1) The soft coal easily absorbs water and expands, and the coal body expands under the action of hydration to produce a volume deformation. The water content of the hole mouth area is high in the process of drilling, which easily leads to the swelling deformation of the coal body in the hole mouth broken area after water absorption.

(2) The soft-coal seam has stronger gas adsorption capacity, and most of the soft-coal seam mines are high gas mines. The gas in the soft-coal seam spills out in large quantities during drilling, breaking the balance of the original stress-gas field, and causing coal instability in the hole crushing area.

(3) Compared with other coal seams, soft-coal seams are more susceptible to the surrounding adjacent layer mining and excavation and other external conditions. At the same time, drilling in a soft-coal seam is also common, which directly leads to the severe disturbance of drill pipe to the pressure relief zone at the hole mouth, as shown in Figure 5, which directly causes the hole collapse in the hole mouth area after drilling back easily in a short time.

Therefore, to reasonably solve the hole collapse problem in the hole opening area of the soft-coal seam, it is necessary to prereinforce the sealing process of boreholes. Based on the traditional sealing process, technical ideas such as concrete spraying support and reinforcement sealing are used.\(^{25,26}\) This paper explores the prereinforce sealing technology of the hole opening of the new sealing section.

3. RESULTS AND DISCUSSION

3.1. Research and Application of “Concentric Ring” Reinforcement and Sealing Technology. 3.1.1. “Concentric Ring” Reinforcement and Sealing Technology. To solve the problem of hole collapse in the soft-coal seam, it is necessary to reinforce the hole in advance. Based on this, the research group proposed a new reinforcing sealing method of “concentric ring”. In a soft-coal seam, from the center of the circle outward along the direction of the aperture are successive “grouting seal rings” and “wall rock hole rings”. The “grouting seal ring” is realized by the grouting process of “two pluggings and one injection”, located in the stress concentration area of the borehole sealing section. The “retaining rock bore ring” is realized by the pregrouting reinforcement process and is located in the crushing area of the...
hole mouth. The physical model of the “concentric ring” reinforced seal is shown in Figure 6.

![Figure 6. Schematic diagram of the “concentric ring” reinforced seal model.](image)

Its basic technical principle is as follows:

First of all, the main idea is to change the broken and unstable “coal hole” in the borehole mouth area of the soft-coal seam into the dense and stable “rock hole”. First, the conventional drill bit is used to drill 5−10 m (the reasonable reinforcement depth is 2 times the width of the roadway by analyzing the law of literature). Then, the reinforcement section is reamed with large holes. After the field test, it is found that the reaming diameter should be increased by 10−20 cm based on the predrilled diameter. Finally, the grouting system is used to reinforce the broken area of the orifice, namely the reinforcement section, and conventional extraction drilling is carried out after the reinforcement section is completely solidified. Finally the “wall rock hole” is formed, which can effectively enhance the stability of the orifice area to prevent the collapse of the hole, as shown in Figure 7.

Based on the completion of the above “wall rock hole”, the grouting system is used to reinforce the sealing grouting of the stress concentration area with “two pluggings and one injection”. The double pressure grouting not only can ensure the early sealing of the leakage cracks at the orifice position but also can effectively seal the cracks in the stress concentration area.

In general, the “concentric ring” reinforcement sealing process not only shortens the sealing length, saving the material such as bag-type sealer, but also ensures the reasonable and orderly drilling and sealing process from a technical point of view.

3.1.2. Field Application Test of “Concentric Ring” Reinforcement Seal Method. The test site is selected on the N2106 belt passage working face of a mining area in Shanxi Province. The coal body solidity coefficient $f < 0.5$ of this working face belongs to the soft-coal seam. N2106 coalface has no special geological structure, the gas content of coal seam is 7.82 m$^3$/t measured on-site, and the total gas emission is 2.16 m$^3$/min.

In the field test, the drilling hole is selected for gas drainage along the coal seam. The drilling hole is oriented to the coal body by the N2106 belt routing work. The design depth of the drilling hole is 130 m vertical to the coal body, and the drilling angle is $-1−2^\circ$ (The spacing between boreholes is greater than 3 m). After the drilling is completed, the grout is timely sealed and the network is closed. Figure 8 shows the layout of the test boreholes. The drilling footage, geological conditions, and gas emission of the two groups of test boreholes are all similar to ensure the accuracy of the field test.

![Figure 8. Layout of the N2106 tape along the groove working surface at the test site.](image)

The field test holes are divided into groups A and B. The test holes in group A adopt the normal drilling mode with the common “two plugs and one injection” sealing technology, and the test holes in group B adopt the new reinforcing sealing technology of “concentric ring”. The grouting of the two groups of test holes is chosen as a CF expansive solidified sealing material. The two groups of test holes were denoted as A1−A10 and B1−B10, respectively.

Combined with the actual situation of the mine and according to the technical requirements, a 140 mm diameter drill bit was selected for the test drilling of group B to drill the prereinforcement area, as shown in Figure 9a and Figure 9b (the extraction hole was 120 mm), and the prereinforcement depth was 6 m. The expansion capsule was used at the orifice (as shown in Figure 9c) to plug, and then grouting was performed to form a “pre-reinforcement rock hole”. The drilling holes in group A were sealed with common “two plugs and one injection” at 16 m, and the drilling holes in group B were sealed with bag-type “two pluggings and one injection” at 6−16 m. The bag-type sealer is shown in Figure 9d, and the downhole field test is shown in Figure 10.
According to the statistics of the hole formation of the test holes, 12 holes in group A were sealed by the ordinary "two pluggings and one injection". It was found that 7 of the 10 effective extraction holes appeared to have hole collapse after drilling back and were sealed after the second draining hole through the hole. Fourteen holes were drilled in group B of the new reinforced seal of "concentric ring", and none of the 10 effective extraction holes collapsed after drilling back. Moreover, due to the smooth and compact hole wall at the orifice location, the time spent in field pipe sealing was greatly reduced.

### 3.2. Field Test Effect Investigation

In the N2106 belt routing work, the extraction concentration of the two groups of test boreholes was tested for three months. The gas concentration test frequency of the borehole was once every 2 days, and the average value was taken after each of the three shifts was tested once on the test day. The field test results are shown in Figure 11 and Figure 12.

After a comparative analysis of test results in Figure 11 and Figure 12, it can be found that the concentration of gas extraction from test boreholes in group A in Figure 11 attenuates significantly after the beginning of extraction. The average concentration of gas extraction is 21.2% on the 30th day of extraction, and below 30% after that. The average concentration of gas extraction on the 60th and 90th days of extraction is only 10.1% and 2.0%.

In Figure 12, the concentration of gas extraction from the test borehole in group B was above 30% in the first 30 days. After 30 days of extraction, the concentration of gas gradually decreased significantly, and the average concentration of gas on the 60th and 90th days of extraction was 18.4% and 10.9%. It shows that the sealing effect of reinforced sealing test borehole with "concentric ring" is better than that of common sealing test borehole with "two plugs and one injection".

To further investigate the new reinforced sealing effect of the "concentric ring", on the 30th day after the extraction, four representative boreholes were selected from the two groups of test boreholes A and B to test the negative pressure at the borehole mouth and calculate the pure gas flow rate. The results are shown in Table 1.
As can be seen from the above table, the negative pressure at the orifice of the test boreholes in group A is significantly smaller than that in group B on the 30th day of drainage, and the maximum negative pressure difference at the orifice of the test boreholes reaches 0.029 m$^3$/min. The pure gas flow of the test boreholes in group A is also significantly smaller than that in Group B, and the maximum pure gas flow of the test boreholes in group B reaches 0.053 m$^3$/min. This further indicates that the sealing quality of the group B test hole is higher.

In summary, it can be concluded from the above field test results that the “concentric ring” reinforcement sealing technology can not only effectively solve the problem of hole collapse after drilling in the soft-coal seam, but also seal the leakage channel more completely due to the influence of two-pressure grouting, and the sealing effect is better than that of the traditional sealing technology. The new reinforcement sealing technology proposed in this paper is aimed at the problem of instability and gas leakage in the drilling of a high-gas soft-coal seam. In the process of drilling sealing, the key sealing parameters, grouting equipment, materials, and working experience have a direct impact on the final sealing effect of the drilling, which is also the focus of the author’s next research.

4. CONCLUSIONS

(1) The mechanical model was solved by combining the strength of the softening zone with the theoretical analysis of the force on the borehole, and it was found that the coal body in the broken zone of the borehole was prone to collapse under the time effect.

(2) A soft-coal seam is prone to instability deformation due to its strong adsorption, easy expansion, and other characteristics. The instability is also due to a drilling deviation causing a violent disturbance on the hole mouth, and the hole collapse is exacerbated after the drilling hole back.

(3) The field application test results in the N2106 belt routing face of a mining area in Shanxi show that the holes in the test holes reinforced by “concentric ring” do not collapse after drilling, and the gas concentration stays above 30% in the first 30 days. The sealing effect is better than that in the test holes reinforced by “two plugs and one injection”.

(4) By comparing the results of negative pressure and pure gas flow at the orifice on the 30th day of extraction, it is found that the maximum pure gas flow of the drilling hole reinforced with a “concentric ring” reaches 0.053 m$^3$/min, which further proves that the sealing quality of the drilling reinforced with “concentric ring” is higher.
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