Coal Structure Characteristics in the Northern Qinshui Basin and Their Discrimination Method Based on the Particle Size of Drilling Cuttings

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ABSTRACT: Coal structure, including primary coal, cataclastic coal, granulated coal, and mylonitized coal, is one of the key factors controlling coal and gas outburst, and it also determines the efficiency of coalbed methane (CBM) extraction. Therefore, it is significant to identify the characteristics of coal structures and to predict them in advance. In this work, the spatial distribution, mechanical properties, and microscopic morphology of the four coal structures from the No. 3 coal seam of the Xinyuan Mine in the northern part of the Qinshui Basin were investigated through the in situ observation in the roadway, the hardness coefficient (f) test, and the scanning electron microscope analysis. Moreover, the drilling cuttings from the gas pressure releasing holes were sampled and sieved, and then, the correspondence between different coal structures and the particle size of the cuttings was analyzed quantitatively based on the Rosin−Rammler model. The result shows that the spatial distribution of the coal structure has strong heterogeneity in the vertical and lateral directions. The f value decreases successively with the increase in coal structure deformation, which indicate that f can directly characterize the coal structure. Furthermore, the relations between f and drilling cutting average particle size (d₀), crushability indicator (n), crushing degree index (λ), and the median diameter (d₅₀) were established. Specifically, the coal deformation degree is positively correlated with the mass fraction of large particles in the cuttings under the same drilling parameters. Overall, as f increases, d₀ and d₅₀ decrease, and n and λ increase. However, parameters d₀, d₅₀, and λ of granulated coal are inconsistent with other coal structures, and mylonitized coal is inconsistent with other coal structures in n, as a result of the coal structure broken characteristics itself and the difference in the stress state between the coal and the drill bit during the rock breaking process. Ultimately, the coal structures determined by the surface CBM well logging curve and the cuttings particle size method were compared, and they have a high degree of coincidence in the distinction between primary coal and tectonic coal.

1. INTRODUCTION

Because of the influence of depositional environment and tectonic movement, coal seams are often of a complicated structure and vary in both vertical and lateral directions. Based on the degree of deformation, the coal structure is divided into two main types: primary coal and tectonic coal. Tectonic coals include cataclastic coal, granulated coal, and mylonitized coal. During the underground coal mining and surface coalbed methane (CBM) extraction, the coal structure is a key factor affecting mining efficiency and gas production. Many scholars have carried out research on the physical properties of tectonic coal. Smyth and Buckley believed that the fracture system in the coal structure is mainly controlled by the areal density and thickness of different coal types. Bustin studied the characteristics of coal seams in the Sydney Basin and found that the damage degree of the coal structure, the effective stress of the

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stratum, and the maceral determine the permeability of the coal seam jointly. Gürdal and Yağcı reported that the location of tectonic coal affects the mechanical properties of the coal seam, and its porosity will absorb more gas, but its low permeability is not conducive to the diffusion and seepage of gas.

The coal structure also widely affects engineering construction, such as drilling, hydraulic fracture propagation, and gas production by drainage and pressure reduction. It is generally considered that the more broken the coal structure, the worse the wellbore stability and the greater the well diameter and the amount of drilling cuttings in the gas extraction hole. Additionally, a thick layer of cement sheath will form around the wellbore, and the initial pressure will increase rapidly during hydraulic fracturing in which granulated coal and mylonitized coal are developed. These may lead to the rupture of cement sheath and engineering failure such as sand plugging. During CBM drainage, both water and methane have the ability to carry coal fines produced in tectonic coals, which is easy to cause the blockage of the production channels, resulting in rapid reduction of productivity. Moreover, the coal fines make fracture close and reduce the desorption range.

Tectonic coal has fast gas desorption rate and large desorption amount and gas internal energy; thus, the development of tectonic coal is one of the important factors for coal and gas outburst. However, coal and gas outburst occur only when the tectonic coal develops to a certain thickness. In particular, the generation, enrichment, and migration of gas are all affected by the coupling effect of tectonic coal and in situ stress, and the tectonic coal induced by compressive faults is more prone to coal and gas outbursts. As can be seen, the studies revealed the controlling effect of the coal structure on coal and gas outburst. Therefore, the identification and prediction of the

Figure 1. Setting of the study area: (a) tectonic outline map of the Qinshui Basin; (b) lithological column of the northern Qinshui Basin; (c) coal seam tectonics of the working face in the Xinyuan Mine; I–VI are six observation points with different coal structure combinations.)
coal structure is particularly significant, especially for drilling along the coal seam. When the in situ stress and gas pressure of the coal seam are higher than the critical value, larger hole diameters and more drilling cuttings will be produced under the same drilling parameters, which implies that the tectonic coal has a higher risk of gas outburst. The staff needs to collect the cuttings generated during drilling and put the cuttings into a closed container to detect the desorption amount and then measure the gas desorption index, desorption rate, and desorption amount. These parameters can predict whether the coal seam has the danger of coal and gas outburst. The gas pressure, gas content, and damage degree of coal seams in different regions are varied, leading to the different desorption rate and desorption amount of the cuttings. Therefore, the value of the cuttings desorption index can be used to determine the risk of gas outburst in coal seam to a certain extent.

At present, well logging methods are used to distinguish and predict the coal structure mostly such as resistivity logging, natural gamma logging, compensated density logging, density logging, sonic time difference logging, compensated neutron logging, and so forth. Besides, Tang, Zhang, and Sun used the dropping hammer method to test the hardness coefficient of coal based on the area force energy theory and classified the coal structure types. Turcotte, Li, Yan, and Li found that the particle size of cuttings has fractal characteristics through statistical analysis. Wang et al. used the geological strength index (GSI) to quantitatively characterize the coal structure through the underground observation in a mine and established the relationship between the GSI and the f value. Tang, Chen, and Yu proposed the Mohr–Coulomb criterion to derive a new formula for the amount of drilling cuttings and analyzed the relationship law between the amount of drilling cuttings, the mean effective stress, and the mechanical parameters. Lv et al. distinguished three types of coal structure in the southern Qinshui Basin including primary coal, cataclastic coal, and granulated coal based on the curve shape of the particle size histogram of drilling cuttings and predicted the spatial location of the tectonic coal in a horizontal CBM well, thus guiding the optimal deployment of perforating and fracturing sections. Most of these research were quantitative analysis of the drilling cuttings amount and the particle size, while there are a few studies on the distribution characteristics of the cuttings particle size with different coal structures, especially for the soft coal seam in the northern Qinshui Basin. Furthermore, previous studies focused on the immediate response of gas or drilling cuttings to the coal structure, but a few reports carried out advanced prediction of the coal structure. After predicting the coal structure, it is possible to take corresponding measures timely and efficiently to prevent coal and gas outbursts at the source.

Xinyuan Mine is a coal and gas outburst mine, which faces the challenge of outburst control during the excavation roadway or working face. Compared with primary coal, the tectonic coal seam with structural deformation has low strength, poor gas permeability, high gas adsorption, fast desorption, and increases risk of coal and gas outburst, which is extremely unfavorable for coal mining. Inspection drilling is carried out in the roadway to measure the relevant parameters to determine whether the roadway has outburst hazards. By analyzing the characteristics of drilling cuttings in the borehole, the coal structure tens of meters or even hundreds of meters in front of the coal head can be predicted. When it is predicted that the dangerous layer of gas outburst will occur, control measures should be taken in advance, which plays an important role in the safety production of coal mines. In this work, the coal structure was observed in the No. 3 coal seam of the Xinyuan Mine in the northern Qinshui Basin. Then, the hardness coefficient of coal was measured, and the drilling cuttings samples from the gas pressure releasing holes were analyzed. Based on the work mathematical relation model between the coal structure and drilling cuttings, the particle size was established.

2. METHODOLOGY

2.1. Geological Setting. The Qinshui Basin have a few large-scale fault structures and are generally affected by a complex syncline in the NNE direction. There are many small folds developed in the basin, and the direction is mainly NNE influenced by the syncline. Larger faults are developed in the marginal zone of the basin, and the direction of the normal faults is mainly NE, NNE, and NEE. Generally, geological conditions inside the basin are simple, and the structures of the basin margin is relatively complex (Figure 1a). The Xinyuan Mine is located to the west of the Taihang Mountains uplift in the north of the Qinshui Basin. The Caogou syncline mainly develops in the east of the mining area, and collapse columns and small faults develop in the west. Because of the tectonic movements of the Indosinian, Yanshan, and Himalayas, the Qinshui Basin has experienced ups and downs, folds, fractures, and deformations. The coal seams have been damaged to varying degrees, and different types of coal structures were formed. The main coal seam of the mine is the No. 3 coal seam, which is located in the middle and the upper part of the Shanxi Formation, and the type of coal is anthracite. The thickness of the coal seam is 0.40–4.75 m, with an average of 2.58 m. The coal seam in the mining area is thick in the middle and thin on both sides, which is a stable and mineable coal seam. The lithology of the roof and floor of the coal seam is not much different, and they are all dominated by mudstone and sandy mudstone (Figure 1).

Based on the parameters such as the degree of coal damage, the basic signs, fracture development, and the strength of the coal, the coal structure can be divided into four categories: primary coal, cataclastic coal, granulated coal, and mylonitized coal (Table 1). Figure 2 shows a typical coal seam section in the Xinyuan Mine, including different coal seam structures and coal structure types.

Scanning electron microscopy (SEM) was performed on the coals with different coal structures sampled from a working face in the Xinyuan Mine shown in Figure 3. The surface of the primary coal is smooth, the fractures are not developed, and the whole is relatively uniform (Figure 3a). The surface of the cataclastic coal is relatively smooth, with two micro fractures developed; coal particles are attached locally, and the whole is relatively complete (Figure 3b). The granulated coal is broken with more small particles distributed, and the overall deformation is more serious (Figure 3c). Mylonitized coal has the highest broken degree, and all small coal particles are closely packed together and are mostly scaly (Figure 3d). Because of excessive effective stress, resulting in complete destruction of the coal and compaction of coal fines, thus the soft coal is formed with small gaps between particles and tight packing (Figure 3e). The coal particles in the soft coal belt are obviously aggregated, but the cohesion is not good, and it is easy to fall off and dye hands. Because of the strong compression in situ stress, there
Table 1. Classification and Characteristics of the Coal Structure

| Coal Structure Types          | Damage Degree                  | Basic Symbol                | Fracture Development Degree                        | Mechanical Strength |
|------------------------------|--------------------------------|----------------------------|--------------------------------------------------|--------------------|
| Primary Structure            | The original structures are basically not damaged | Mostly strip-shaped, and the fractures are vertical | Fractures with a small amount of vertical layer developed | Highest            |
| Catastrophic Coal            | The coal is damaged, fractures are developed, and there is a displacement surface. | The layers are destroyed, but the shape of layers can still be seen | Multiple groups of intersecting joints are developed | Medium             |
| Granulated Coal              | The original structure is damaged; mostly in the form of granules or strips | The layers have basically disappeared, it is difficult to identify, and the wrinkled surface is often seen | Exogenous fractures are extremely developed, and the coal is cut into pieces | Lower              |
| Mylonitized Coal             | The coal has been damaged to the greatest extent, and there is no original structure | The layers disappear completely, and the slip surface increases. It is powdery, and the luster is dull | Exogenous fractures have been strongly deformed and cannot be identified, and crumpled surfaces and slip surfaces can be seen locally | Lowest             |

3. RESULTS

3.1. Spatial Distribution. The coal seam section is divided based on the macroscopic coal lithotypes and the coal structure, and the observed orientation and density of natural fractures are measured. The variation of coal seam thickness, the thickness of the coal seam, and the orientation of fractures are measured, because of the limitations of observation space and the thickness of the coal seam. The thickness of the coal seam is 2.0 m, and the variation of coal seam thickness, the thickness of the coal seam, and the orientation of fractures are measured. The observed orientation and density of natural fractures are measured, because of the limitations of observation space and the thickness of the coal seam.

3.2. Hardness Coefficient Test. Compared with other rocks such as sandstone and mudstone, coal has unique mechanical properties, especially when testing the compressive strength, shear strength, and tensile strength. Therefore, a comprehensive parameter hardness coefficient is proposed for the characterization of these mechanical properties of coal. The coal hardness coefficient is a relative index reflecting the mechanical properties. The larger the value, the more stable the coal is, and the easier it is to extract coal. The hardness coefficient method is used to test the value. First, the sampled coal is obtained through the roadway or working face. The sample size is approximately 1/10 of the limit of uniaxial compressive strength. Therefore, a comprehensive parameter hardness coefficient is proposed for the characterization of these mechanical properties of coal.
Figure 2. Typical coal seam section with different coal lithotypes and coal structures in the Xinyuan Mine (modified from Lyu et al.5).

Figure 3. SEM analysis of the surface morphology of different coal structures: (a) primary structural coal; (b) cataleastic coal; (c) granulated coal; (d) mylonitized coal; (e) soft coal; (f) coal fine.

Figure 4. Six (from I to VI) types of coal structure combinations observed and summarized at the tunneling face.
The observation result shows that the coal structure of the No. 3 coal seam has the characteristics of vertical differentiation, which can be summarized into six different combinations in general (Figures 1c and 4). Tectonic coals prone to outburst mainly refers to granulated coal and mylonitized coal, in addition to soft coal and coal fine belt. At the front end of the tunneling face, the distribution of tectonic coal is mostly located in the lower part of the coal seam. With the increase in the footage of the tunneling face, the tectonic coal gradually develops in the middle of the coal seam, which shows that it has discontinuity in the horizontal spatial distribution. This discontinuity is mostly controlled by the small structures such as faults and folds in the coal seam. For instance, at the footwall of the normal fault, broken zones with fractures and tectonic coals are developed.

Coal structure combination type I: The obvious characteristics of the type are that the middle and lower parts of the coal seam are relatively broken, and the coal deformation is relatively serious. Among them, the cataclastic coal in the lower part and the mylonitized coal at the bottom are in a gradual transition, and there is no obvious boundary. Additionally, there are 1−2 thin layers of gangue in the coal seam. The coal structure on both sides of the gangue is relatively complete without obvious exogenous fractures. The gangue layer near the bottom of the coal seam has a certain sealing effect on the coal seam gas.

Coal structure combination type II: The overall structure is similar to type I. Especially, there are many natural exogenous fractures developed, some of which are filled with calcite. Furthermore, the natural fractures can pass through several coal layers, and the gangue has a certain blocking effect on the extension of natural fractures. Therefore, this kind of fracture does not penetrate the whole coal seam.

Coal structure combination type III: In this type, the natural exogenous fractures in the cataclastic coal can be cut through and extended to the primary coal at the top. Different from the coal structure of type II, the tectonic coals in this type move up obviously. Because hydraulic fractures are difficult to extend significantly in thick tectonic coal with strong deformation and extrusion, the fracturing fluid distribution in the coal seam is uneven. Furthermore, a layer of low-permeability gangue develops in the lower part of the tectonic coals, which is a greater risk of coal and gas outburst.

Coal structure combination type IV: This type is similar to type III, and the mylonitized coal layer in the middle of the coal seam is thinner, and the natural exogenous fractures of the
cataclastic coal in the upper part are more developed. The vitrinite band, which is the inner layer of the cataclastic coal, is cut through by the fractures. The lower part of mylonitized coal is gangue and scaly granulated coal in turn.

Coal structure combination type V: This type is much different from coal structure type IV. In the section, the gangue layer with low permeability is thin and easily penetrated by the injected fluid. The coal fine band has a certain slurry effect on the fluid and increases the flow resistance of the fluid. However, the coal fine band generally has poor continuity and is only locally distributed in a lenticular shape; also, it has little effect on fracture propagation during the hydraulic fracturing.

Coal structure combination type VI: There is a soft coal layer with the thickness of 10−15 cm in the middle and lower parts of the coal seam, where coal and gas outburst is easy to occur. However, cataclastic coal and primary coal are relatively developed in the coal seam, where hydraulic fractures can form a fracture network with natural fractures to communicate the smaller-scale gangue layer and the soft coal layer, thus significantly reducing the risk of coal and gas outbursts.

3.2. Hardness Coefficient. As shown in Table 2 and Figure 5, the samples #1−#4 are primary coals with the f value between 0.60 and 0.85. Because of the well development of cataclastic coal in the No. 3 coal seam, which is also the main layer for gas pressure relief deployment, the large quantity of #5−#15 is cataclastic coals, and the f value is between 0.42 and 0.56. Samples #16−#18 are granulated coals with the f value between 0.34 and 0.37. Samples #19−#21 are mylonitized coals with the f value less than 0.31. The f values of four kinds of coal structure samples collected from different layers of a coal seam in the same mine gradually decrease, with the increase in the damage degree of the coal structure.

There are also many coal mines in the southern Qinshui Basin, where China’s largest demonstration base for the CBM industry has been established. The No. 3 coal seam in this area is mainly composed of primary coals, and its hardness coefficient is generally greater than 0.80. In addition, cataclastic coal is also developed in large quantities, whose hardness coefficient is concentrated in 0.5−0.6, the hardness coefficient of granulated coal is less than 0.4, and the mylonitized coal is less developed. The comparison shows that the tectonic stress in the north of the basin is relatively strong, and the mechanical strength of different coal structures is lower than that in the southern basin. The coal structure directly affects gas accumulation. Hence, there are a large number of coal and gas outburst mines in the northern basin. On the other hand, broken coal is not conducive to the stability of drilling wellbore, and artificial channels after hydraulic fracturing cannot communicate effectively, which makes it difficult to form a large-scale pressure drop funnel in the CBM well zone, resulting in low CBM production generally.  

3.3. Particle Size of Drilling Cuttings. Based on the mass percentage of cuttings (Table 2), the particle size distribution histogram of cuttings produced by different coal structures was drawn (Figure 6). For primary coal, the drilling speed is uniform during the drilling process, and the bit grinding the coal is stable. The result shows that the proportions of cuttings with the particle size greater than 2.8 mm and less than 0.25 mm are close, and the particle size distribution of 1−2.8 mm accounts for the most. Generally speaking, the particle size is relatively concentrated, and the drilling footage per unit time is relatively minimum. For cataclastic coal, coal collapse is common, and the particle size distribution of drilling cuttings is uneven. The proportion of the cuttings with the particle size greater than 2.8 mm is significantly greater than that of the cuttings with the particle size of 0.25−0.15 mm, and the proportion of the particle size of 1−2.8 mm is the largest. The particle size distribution is relatively concentrated, and the drilling footage per unit time is slightly less than that of primary coal. For granulated coal, there are more natural coal fines in the cuttings, and the hole wall collapses seriously. Most of the cuttings are flake, and the proportion of the large particle size and the small particle size is basically close. The number of particle size with the largest mass fraction is significantly less than that of cuttings with other coal structures, and the footage per unit time is also large. For mylonite coal, the content of coal fines is high, the hole wall collapse is the most serious, and the particles in the cuttings from the original coal are obvious. The proportion of the cuttings with the particle size greater than 2.8 mm is the highest, the particle size concentration degree is also relatively low, and the drilling footage per unit time is the largest.

In addition, the average particle size of cuttings with different coal structures was studied. Based on the mass distribution histogram of the particle size, the average particle size of the cutting is expressed as the following equation:

\[ d_0 = \frac{1}{2} \sum_{i=1}^{n} \Delta Q_i (x_i + x_{i-1}) \]  

in which \(d_0\) is the arithmetic volume average particle size, \(x_i\) is the upper limit of the \(i\)th particle size interval, \(x_{i-1}\) is the lower limit of the \(i\)th particle size interval, and \(\Delta Q_i\) is the relative amount of the \(i\)-th particle size \(\Delta x_i\).
Overall, the larger the $f$ value is, the smaller the $d_0$ is (Figure 7a). However, the particle diameter feature of the granulated coal and the other three types of the coal structure has a difference. After the cutting of granulated coal are removed, the particle size and the hardness coefficient of the other cutting have a good linear negative correlation relationship, and $R^2$ can reach 0.9 (Figure 7b). The phenomenon is related to the evolution of the coal structure formation. To clarify, the granulated coal is now extremely developed with fractures and is cut into uniformly dispersed blocks. Under the action of bit circumferential force, it is broken into a smaller particle size. Therefore, among the four types of coal structures, granulated coal is characterized by a small hardness coefficient and a small particle size.

4. DISCUSSION

4.1. Quantitative Analysis Based on the Rosin–Rammler Model. As shown in Figure 6, the proportion of the large particle size in the cuttings produced from primary coal is the smallest, and its particle size concentration degree is the best. The proportions of the large particle from cataclastic coal and granulated coal have gradually increased; the large particle cuttings from the mylonitized coal account for most, and its concentration degree is the worst. Therefore, it can be concluded that the broken zones of the coal structure have a certain correlation with the proportion and the concentration degree of different particle size of cuttings. The Rosin–Rammler model (R–R model) is used to quantify such a feature of cuttings. The R–R model is expressed as the following equation:

$$F(d) = 1 - \exp\left[-\left(\frac{d}{d_{50}}\right)^n\right]$$

in which $F(d)$ is the sum of mass percentages of all particle sizes less than a certain particle size $d$, mm; $d$ is the particle size, mm; $d_{50}$ is the median diameter, that is, $d_{50}$ is the particle size corresponding to the cumulative weight distribution at $F(d) = 0.5$, mm; $n$ is the crushability indicator, which reflects the
concentration degree of the particle size; the larger the \( n \) value, the more the particle size distribution.

Eq 2 can be deformed as follows:

\[
y = \ln(-\ln[1 - F(d)]) = n \ln d + \lambda \tag{3}
\]

\[
\lambda = -n \ln(d_{50}) \tag{4}
\]

in which \( \lambda \) is the crushing degree index, and the larger the \( \lambda \) value is, the more the number of the small particle size is generated in the cuttings. Based on the linear relationship between the \( x(\ln d) \) and \( y \) in eq 3, the slope \( n \) and intercept \( \lambda \) are calculated by fitting. Then, \( d_{50} \) can be obtained using of \( \lambda \) and \( n \) in eq 4. The plotting result shows that the R\(^2\) of the linear regression equation is more than 0.95, indicating a high degree of fit (Figure 8).

Because of the correspondence between the hardness coefficient and different types of coal structures, \( f \) can be used as a characterization parameter for different types of coal structures. Based on the R–R model, it is found that the \( n \) value of mylonitized coal is significantly larger than that of other coal structures. Except for mylonitized coal, the \( n \) value decreases with the reduction of the \( f \) value, indicating that the greater the deformation degree of coal, the more irregular the particle size distribution, and it will not be concentrated in a certain particle size range. There is an obvious positive correlation between the \( \lambda \) value and the coal structure. The more complete the coal is, the smaller the cuttings produced by the drill bit under the breaking action is, and it is not restricted by geological factors. The median diameter \( d_{50} \) has an obvious negative correlation with \( d_0 \), which is consistent with the response of \( d_0 \) to the coal structure (Figure 9).

4.2. Rock Breaking Mechanism Affected by the Coal Structure. During the bit drilling in the coal seam, the coal in front of the bit has an impact speed forward under the action of the bit rotation, resulting in normal stress \( P_1 \). At the same time, under the action of the wind as the circulating medium, the coal in front of the bit will also receive normal stress \( P_2 \). In addition, when the bit rolls, the tangential stress \( P_3 \) of the drill teeth acts on the hole wall. To illustrate, the axial force of the drill bit acts on the coal wall, and the cuttings are generated when the coal is broken. The axial force generates compressive stress, and the tangential force forms tensile stress around the hole. Therefore, stress zones are formed including the normal stress zone, the tensile stress zone, and the transition zone between the normal stress zone and the tensile stress, which is subjected to the joint action of the two forces (Figure 10). Originally, different coal structures are distributed in the coal seam; at the same time, the force is balanced. When the coal seam is disturbed during the drilling construction, the stress balance is broken. Then, the stress around the hole is redistributed.

![Figure 9](image1.png)

**Figure 9.** Relations between the coal structure represented by the hardness coefficient \( f \) and different parameters including (a) \( n \) (b) \( \lambda \) (c) \( d_{50} \) and (d) the relation between \( d_{50} \) and \( d_0 \).

![Figure 10](image2.png)

**Figure 10.** Schematic diagram of the coal seam force and the particle size distribution of drilling cuttings with different coal structures when drilling along the coal seam.
However, when the stress exceeds the maximum limit value that the coal can bear, the coal is damaged and the cuttings are produced.\textsuperscript{51,52} Depending on the strength of the original coal, the properties of the cuttings amount and the particle size are also different (Figure 10).

The primary coal has high strength and uniform mechanical properties. Its drilling cuttings are mainly produced by rock breaking effect of the normal stress of the drill bit. Under the influence of the single force, the cuttings produced from the primary coal are generally small particles, and its distribution is relatively concentrated, which is close to the normal distribution characteristics. There are some fractures or joints developed in the cataclastic coal, which are also mainly affected by the normal stress. Compared with the primary coal, the particle size of the cuttings produced from cataclastic coal is slightly larger, and the particle size distribution is not as regular as that of the primary coal, so its $\lambda$ and $n$ is less than that of primary coal, while $d_{50}$ is greater than that of primary coal. For the granulated coal, the broken degree is high, and a large number of loose coal fines are mixed between the broken fragments. In addition to the normal stress, the loose coal is also subjected to the circumferential tensile stress, that is, double stress. The particle size of the cuttings produced under the action of normal stress is larger than that of the cataclastic coal. Moreover, under the action of the tensile stress, the coal fines automatically fall and disperse, resulting in a large number of smaller particles. Therefore, the particle size distribution of cuttings from granulated coal is not concentrated, the $n$ value is slightly lower than that of cataclastic coal, and the $d_0$ and $d_{50}$ are not too large, which are close to that of the cataclastic coal. Additionally, the small particle size is overall larger than that of cataclastic coal, so the $\lambda$ value is larger. For the mylonitized coal, there are the most coal fines. However, unlike granulated coal, a considerable part of the coal fines has been reunited into agglomerates under the extrusion of greater effective stress during the formation of mylonitized coal, and the agglomerates are mixed in the particles, which are difficult to break under the small force, but is relatively soft on the whole. Under the influence of the shear stress, the mylonitized coal fall into lumps, with the largest $d_0$ and $d_{50}$, but the particle size distribution was unstable, ranging from large lumps to small coal fines. On the contrary, the small particle size of drilling cuttings from the mylonitized coal is not the lowest (Figure 9).

In the southern Qinshui Basin with successful CBM development, the underground observation found that in addition to mechanically broken coal particles, there are coal fines in the coal itself. Moreover, the particle size of coal fine aggregates with the largest proportion is larger than 2 mm, and the mass fraction is more than 50%. Among the coal fines with the particle size less than 2 mm, the coal fines with the particle size less than 1 mm is much more than that with the particle size of 1–2 mm.\textsuperscript{44,53} This phenomenon is consistent with the small particles contained in the tectonic coal in the northern basin, but the mechanical strength of the coal seam in the northern basin is one grade lower, leading to the more unique characteristic of the particle size of the cuttings.

4.3. Case Verification of the Drilling Cuttings Method.

During collecting drilling cuttings in the coal mine, actually, it is often difficult to obtain all cuttings completely. On the other hand, it is impossible to determine the hardness coefficient of coal in the deep hole directly. At this time, the method of measuring the particle size of the cuttings has more advantages than the method of measuring the amount of the cuttings. In addition, the location of the cuttings generated is corrected according to the lag time.\textsuperscript{3} To verifying the drilling cuttings method, the coal structure reflected by the logging curve is compared with the coal particle size based on the R–R model. Specifically, CBM wells A and B were drilled vertically to the coal seam in the surface, and logging was performed. Later, when the roadway was excavated to the vicinity of the two wells, gas pressure releasing holes were deployed in advance, which drilled in the middle part of the coal seam. When the target positions A1 and B1 of gas pressure releasing holes were close to wells A and B, particle size analysis was performed by collecting the cuttings in the holes. Table 3 shows the three parameters of $\lambda$, $n$, and $d_{50}$ of the cuttings from the holes.

| Table 3. Parameters of Cuttings from Gas Pressure Releasing Holes Used for Verification |
|-----|----|----|----------------|
| drilling cuttings | $n$ | $\lambda$ | $d_{50}$ | coal structure (R–R model) |
| A1  | 1.45 | −0.35 | 1.28 | primary-cataclastic coal |
| B1  | 0.96 | −0.92 | 2.60 | mylonitized coal |

The calculating result shows that the $\lambda$ value of the cuttings from A1 is $-0.35$, the $n$ value is $1.45$, and the $d_{50}$ value is $1.28$. Correspondingly, the values of the cuttings from B1 are $-0.92$, $0.96$, and $2.60$. The characteristic parameter values of drilling cuttings of the two samples are significantly different. Through the analysis of the quantitative relationship between the coal structure and drilling cuttings based on the R–R model, it is considered that the coal seam at the A1 developed primary-cataclastic coal and the coal seam at the B1 is mylonitized coal, which has gas outburst risks.

The logging curve of the well A (Figure 11a) indicates small changes of the borehole diameter and the natural gamma ray on the whole. The comprehensive analysis the coal seam is primary coal. However, the natural gamma ray at the bottom of the coal seam increases, the resistivity from investigate induction log decreases, and the density greatly decreases, which indicates the tectonic coal within 0.7 m of the bottom plate. In the logging curve of the well B, the borehole diameter in the middle of the coal seam is obviously enlarged, the density is lower, and the acoustic time difference is larger obviously. Therefore, it is judged to be tectonic coal, with 1−1.5 m away from the floor (Figure 11b). In fact, observations were also made during the tunnel excavation process. The results showed that the coal seam around the well A had good integrity, mainly developed primary structural coal and local cataclastic coal. In the contrary, the granulated coal and mylonitized coal were developed in the middle of the coal seam of the well B. Therefore, the method of predicting the coal structure by the particle size characteristics of drilling cuttings has high reliability.

5. CONCLUSIONS

(1) The coal structure of the No. 3 coal seam in the Xinyuan Mine in the northern Qinshui Basin has strong spatial heterogeneity. There are more coal fines in granulated coal and mylonitized coal by SEM, and the compaction of coal fines in the mylonitized coal is relatively tight, which is more consistent with the macroscopic observation. The hardness coefficient ($f$) of primary structural coal, cataclastic coal, granulated coal, and mylonitized coal decreases in turn, whose range is 0.60−0.85, 0.42−0.56, 0.34−0.37, and <0.31, respectively.
The particle size of drilling cuttings with four kinds of coal structures is significantly different, under the same drilling parameters including the bit, speed, and medium. The $f$ value is negatively correlated with the mass fraction of large particles and the average particle size. Based on the Rosin–Rammler model, the crushability indicator ($n$) decreases with the decrease in the $f$. There is an obvious positive correlation between the crushing degree index ($\lambda$) and the $f$ value. Specifically, the granulated coal is subjected to the dual action of normal stress and tensile stress, and the proportion of both large particles and small particles in the cuttings is relatively high.

Figure 11. Logging curves in the coal seam section of two CBM wells: (a) Well A and (b) Well B.
(3) The logging curves of two surface wells were compared with the drilling cuttings method of underground pressure releasing holes, and both of them were consistent in distinguishing the two main categories of primary coal and tectonic coal. Therefore, the drilling cuttings method is a fast and accurate method for predicting the coal structure, which provides a prospect for advanced warning of coal and gas outbursts controlled by tectonic coal.

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**Notes**
The authors declare no competing financial interest.

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