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Relationship of fractures in coal with lithotype and thickness of coal lithotype

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Abstract. The fractures in coal are the main migration and output channels of coalbed methane, directly influencing the permeability of the coal seams. It is of great significance to study the effect of fracture distribution in coals on the permeability of coal seam. The development rules of endogenetic and exogenetic fractures are different among various coal lithotypes. There is also difference in the fracture density for the same lithotype with different thicknesses. Through the observation and description of the macroscopic fractures in coal and the origin of fractures in coal, the effect of the coal lithotype and its thickness on fracture development in coal was discussed. It was found through the study that the density of fractures in vitrain band was the maximum for the same coal rank and thickness, followed by clarain band. There were few fractures developed in the durain band. However, the changes of fracture density in three types of bands presented different declining trends for low, medium and high coal rank. There were no fractures developed in the fusain. There were three variation patterns for the fracture densities at the same coal rank and coal lithotype: linear decrease, nonlinear decrease, and first decrease then remaining unchanged. However, the overall trend was that the fracture density decreased with the increase of thickness of coal band for the same coal rank and coal lithotype.

Keywords: coal; fracture; cleat; coal lithotype; thickness; fracture density

1. Introduction

Coal seam is the generating layer and reservoir of coalbed methane, featured by strong heterogeneity. It is of great significance to study the fractures in coal for the exploration and development of coalbed methane and safe production of coal mines. On the one hand, as the main flow channel of coalbed methane, fractures in coal directly influence the permeability and gas production of the coal seam. The extension direction and development degree control the well spacing and orientation in the development of coalbed methane. It is one of the core contents of the evaluation of coal reservoirs for the exploration and development of coalbed methane (Durucan and Edwards 1986, Karacan and Okandan 2000, Wang *et al*. 2004, Chatterjee and Pal 2010, Paul and Chatterjee 2011a, b, Meng *et al*. 2011). On the other hand, the fracture development leads to the coal crushing, strength reduction, and decreases in compressive strength of coal pillar

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and support ability (Ting 1977). Meanwhile, the density, orientation, connectivity and mineral filling of fractures are directly related to the gas drainage effect. Therefore, understanding the distribution of fractures is conducive to reduce the hidden risks in the production of coal mine (Gamson *et al*. 1993).

As the main basis for the classification of fractures in coal, the origin of fractures has always been the focus of study. For the origin of the fractures, methods and areas of study vary, researchers obtained different understandings of the fracture origin, including the shrinkage of gelled materials (Gresley 1892, Steeg 1942, Ting 1977, Spearsa and Caswell 1986, Daniels and Altaner 1990, Levine 1996, Harpalani and Chen 1997, Laubach *et al*. 1998, Su *et al*. 2001, Bi *et al*. 2001, Zhang *et al*. 2002, Zhong 2004, Dawson and Esterle 2010, Kumar *et al*. 2011), fluid pressure (Secor 1965, Segall 1984, Wang *et al*. 1996, Laubach *et al*. 1998, Pollard and Aydin 1998, Bi *et al*. 2001, Su *et al*. 2001, Zhong 2004, Dawson and Esterle 2010) and in-situ effective stress (Steeg 1942, Price 1959, Ting 1977, Spearsa and Caswell 1986, Daniels and Altaner 1990, Wang *et al*. 1996, Laubach *et al*. 1998, Pollard and Aydin 1998, Su *et al*. 2001, Bi *et al*. 2001, Zhang *et al*. 2002, Zhong 2004, Rippon *et al*. 2006, Dawson and Esterle 2010, Kumar *et al*. 2011, Paul and Chatterjee 2011a, Paul and Chatterjee 2011b).

It is considered after reviewing the above hypotheses that the fractures in coal are formed by the combined action of internal driving force and external stress. Internal driving force is the fundamental reason for the formation of fractures.There are two types of stress that consist the internal driving force for the formation of fractures in coal: (1) the inner tension produced due to the uniform volume shrinkage during a series of physical and chemical changes to the structure of coal body, such as matrix dehydration and devolatilization. These changes are controlled by temperature and pressure in the coalification process; (2) The local high pressure of fluid produced by the original fluid as well as accumulated fluids in the coal body produced in the coalification process and not yet escaped. Such processes are controlled by temperature and in-situ stress. As the main influence factor of the fracture development (especially the exogenetic fractures), the external stress has close relations with the parameters and types of fractures. The external stress responsible for the formation of fractures in coal includes the original in-situ stress and tectonic stress of coal seam. When the resultant force of original in-situ stress on coal body and tectonic stress are greater than the strength of the coal body, the exogenetic fractures are generated. The distribution of stress field determines the combination types and orientation of fractures.

The fractures in coal were classified according to different classification criteria on different scales (Steeg 1942, Price 1959, Ting 1977, Gamson *et al*. 1993, Wang *et al*. 1996, Zhang *et al*. 2002, Su *et al*. 2002, Rippon *et al*. 2006, Dawson and Esterle 2010, Moore 2012) (Table 1). Although different researchers adopt various classification schemes for the fractures in coal, they generally reach the following consensus:

(1) Fractures in coal can be divided into macro fractures and micro fractures depending on the scales. Macro fractures can be observed with the naked eye or magnifying glass. The micro fractures need to be observed under the optical microscope.

(2) Fractures in coal can be divided into endogenetic and exogenetic fractures, according to the origin (Fig. 1). The endogenetic fracture is also called cleat, usually occurring in two sets. The two sets of cleats are perpendicular to each other in most cases and perpendicular to the bedding plane. The endogenetic fractures develop in the band of a certain coal lithotype. The height of fracture is smaller than the thickness of band as the carrier. Exogenetic fractures generally run through a plurality of bands, even penetrating the

ppartings. The fracture height and length are significantly greater than those of endogenetic fractures. It is usually considered that the endogenetic fracture is the product of the uniform shrinkage of gelled materials in coal and expansion of high pressure fluid. The exogenetic fracture is mainly affected by the tectonic stress and human factors.

(3) Endogenetic fracture (cleat) can be divided into face cleat (main fracture) and butt cleat (secondary fracture), according to the sequence of fracture formation, developmental morphology and distribution characteristics. The set of cleat formed earlier with long extension and good development is called the face cleat. The cleat formed later with short extension and usually terminated between the face cleats is called the butt cleat (Fig. 2).

Table 1 Classification schemes of fractures in coal by different scholars

Author	Object for classification	Classification basis	Classification scheme
Steeg (1942)	Fractures in coal	Developmental morphology and distribution characteristics	Face cleat Butt cleat
Price (1959)	Fractures in coal	Mechanical properties	Tension joint Shear joint
Ting (1977)	Fractures in coal	Developmental morphology and distribution characteristics	Primary cleat Secondary cleat
Gamson (1993)	Fractures in coal	Different scales	Macrofractures (face cleat, butt cleat and 3rd cleat) Microfractures (vertical microcleat, horizontal microcleat, blockfracture, conchoidal fracture, stripes)
Wang *et al*. (1996)	Frctures of several microns to a few centimetres in the coal reservoirs	Size and occurrence of fractures and relationships with the carrier	Microfractures Endogenic fractures
Zhang *et al*. (2002)	Microfractures in coal	Development characteristics and genesis of fractures	Endogenetic fractures (dehydration fractures, condensation fractures and static fractures) Exogenetic fractures (tensile fractures, pressure fractures, shear fractures , relaxed fractures)
Su *et al*. (2002)	Fractures in coal	Morphology and genesis	cleats, exogenetic fractures and inherited fractures
Rippon (2006)	Fractures in coal	Developmental morphology and distribution characteristics	Main cleat Subsidiary cleat
Dawson (2010)	Fractures in coal	Development position of fractures	Master cleat Single vitrain layer cleat Multiple vitrain layer cleat Durain layer cleat
Moore (2012)	Fractures in coal	Genesis	Natural fractures Secondary fractures

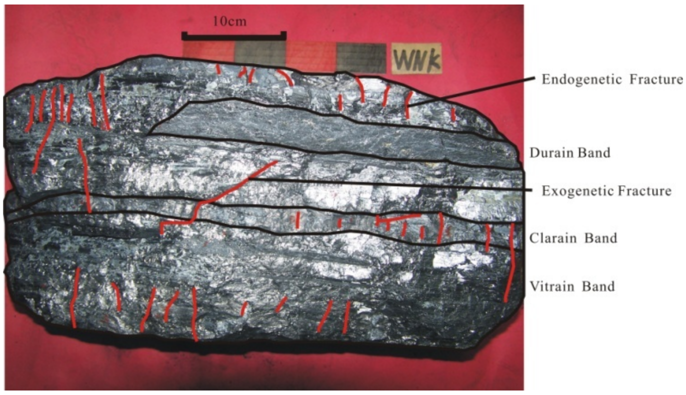


Fig. 1 Distribution diagram of fractures in anthracite (WNK)

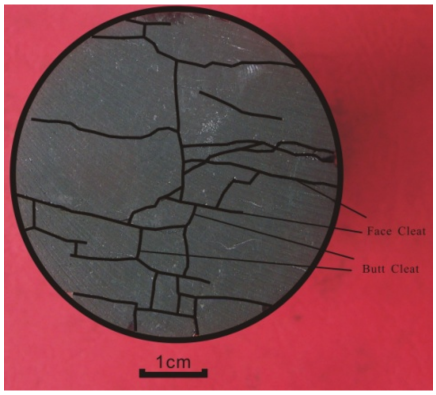


Fig. 2 Diagram of the types of cleat combination in coal core of JCK

2. Relationship between fractures in coal and coal lithotype

Coal lithotype is the basic unit in classification of coal that can be distinguished with the naked eye, including vitrain, clarain, durain and fusain. Vitrain has the deepest color and strongest glint, with uniform texture. The glint and uniformity of clarain are all inferior to those of vitrain. There is often the phenomenon of mutual transition between the clarain and durain. The durain is dense and hard and not easily broken with dim glint and non-uniform thickness of layer. Fusain is greyish black and porous. It stains the finger. The difference in coal lithotypes results in different developments of fractures. The study on the development characteristics of fracture for different lithotypes is crucial for the prediction of reservoir permeability and division of superior coalbed methane blocks. It should be noted that a certain bulk coal sample should be taken as the research object when the lithotype is determined. In a vertical section of the coal sample, the coal lithotype can be divided into four types, according to the glint and development characteristics. They are vitrain, clarain, durain and fusain. There is no comparability for the bulk coal samples from different areas as far as the coal lithotype is concerned.

The coal samples in this study were mainly collected from typical coal mining areas in Inner Mongolia, Shanxi, Hebei and Henan. The fresh section showing the vertical beddings was observed and described in details (Fig. 1). Different coal lithotypes were differentiated. The thickness, coal properties and densities were measured. For cleat density measurement at the above coalfield, the following method is adapted: (1) clean the surface of the coal; (2) identify the coal lithotype of each bands; (3) measure the thickness of the bands and observe the fractures by ruler and magnifying glass; and (4) record and organize the date. The linear density of a band over a certain length was considered as the fracture density. The detailed observation data are shown in Table 2. The relationship of the fracture density of coal samples with different coal rank with coal lithotype is shown in Fig. 3.

The difference in average fracture density between vitrain, clarain and durain in long flame coal (BDK) was the most obvious for the same thickness of band. The ratio reached 4:2:1, which showed a good linear relationship. The difference in average fracture density between different coal lithotypes in fat coal (PMSK) was obvious. The fracture density in the band of vitrain was greater than that of clarain. The fracture density in the clarain band was obviously greater than that

Table 2 Observation data of the fracture development in different lithotypes

Sample name	Coal rank	Coal lithotype	Thickness of band /mm	Density of fractures / 10cm	Average density of fractures / 10cm
BDK	Long flame coal	Vitrain	15	24.3	24.3
		Clarain	15	10.0	10.0
		Durain	15	5.7	5.7
PMSK	Fat coal	Vitrain1	10	17.0	15.3
		Vitrain2	10	16.0	
		Vitrain3	10	12.9	
		Clarain1	10	9.0	12.9
		Clarain2	10	16.7	
		Durain	10	5.0	5.0
WNK	Anthracite	Vitrain1	20	11.0	11.5
		Vitrain2	20	12.0	
		Clarain1	20	10.0	10.5
		Clarain2	20	11.0	
		Durain	20	10.0	10.0

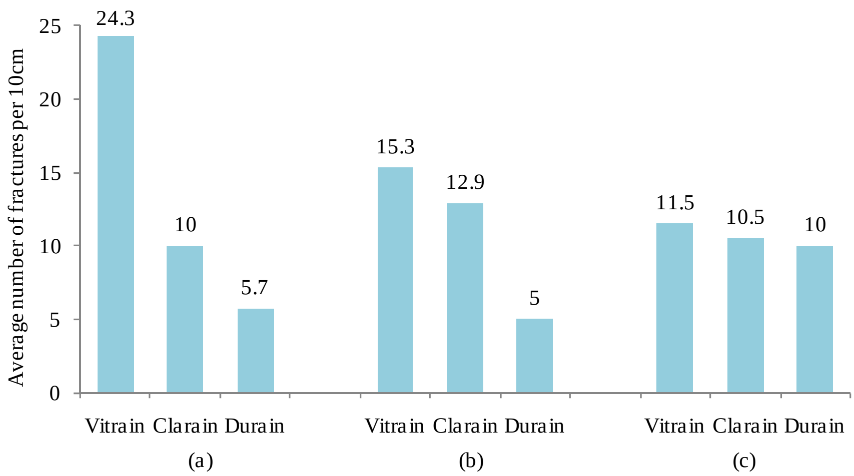


Fig. 3 Relationship between the fracture density of coal samples with different coal rank and coal lithotype: (a) Long flame coal (BDK); (b) Fat coal (PMSK); (c) Anthracite (WNK)

of durain band. The ratio of fracture density in vitrain, clarain and durain was about 3.1:2.6:1. The fracture densities between different coal lithotypes in anthracite (WNK) were only slightly different. The ratio of the fracture density of vitrain, clarain and durain was 1.15:1.05:1. The fractures were not found in the fusain of the above coal samples.

It was found through the observation of macroscopic fractures of coal samples that the fracture densities of different coal lithotypes followed the consistent variation rule for the same thickness of band, in the direction perpendicular to the bedding plane of coal samples with low, medium and high coal ranks: vitrain > clarain > durain. There were no fractures in fusain. For the same thickness of band, the fractures in the vitrain band were most developed for different coal lithotypes. The fractures in the clarain band were well developed, and those in the durain band were developed. However, the difference in fracture development in the vitrain, clarain and durain bands of coal samples with low coal rank was the most obvious. There was an obvious declining trend. The difference in fracture development of coal samples with medium coal rank was obvious with the changing coal lithotypes. The difference in fracture development of coal samples with high coal rank was less obvious with the changing coal lithotypes. The density of fractures for the three different lithotypes shows little variation.

The coal lithotype is affected by the maceral of coal. Therefore, the effect of coal lithotype on fracture development is reflected by the effect of maceral on fracture development to a large extent. According to the color, reflectivity, projection, morphology and structural characteristics of organic constituents of coal, the maceral of coal falls into three categories, vitrinite group, exinite group and inertinite group (Zhang *et al*. 2001). The contents of macerals vary with the coal lithotypes. The content of minerals in the vitrain band was the lowest, and the composition of macerals was uniform. The vast majority was vitrinite. The macerals of the clarain band were more complex than those of the vitrain band. However, the content of vitrinites still accounted for the most part (Wang and Chen 1995). Compared by the durain band, clarain coal band had higher content of vitrinites and lower content of exinites. There were more inertinites in the durain and fusain but fewer vitrinites. The factors affecting the fracture development for different macerals and coal lithotypes are mainly the hydrocarbon generating potent macerals, preservation of the gas generated and mechanical properties of the coal body. It is known from the above analysis that the fluids produced in the coalification gathered continuously, and were finally released, which was the main reason for the formation of endogenetic fractures. In the vitrain band dominated by homogeneous vitrinites with low residual porosity due to the presence of plant cells, the homogeneous macerals led to the gas production reaching the maximum at a certain time point. The scarcity of inorganic minerals is not conducive to the gas discharge and the strength of coal body remains at a low level (Wang *et al*. 1996). Therefore, it is likely that the fluid pressure formed by the gas generation exceeds the ultimate strength to fracture the coal body to form the tensile fractures along the vertical direction of bedding. While in the clarain band with complex composition of macerals, the amounts of gas generated from different constituents in different stages were different. Therefore, it is difficult to form the overlapping peaks of gas production. The instantaneous fluid pressure might be very high. On the other hand, the large amount of inorganic minerals provided favorable conditions for the discharge of gas and increased the strength of coal body. Therefore, the density of fractures in the clarain band was smaller than that in the vitrain band. In the fusain, the gas generation efficiency is low, which not conducive to the preservation of gas. In the meantime, it is difficult to produce high-pressure fluid element. Moreover, the higher mechanical strength makes it difficult for the fluid elements to break through to form the fractures (Wang *et al*. 1996). As a result, there was no development of endogenetic fractures in the fusain.

3. Relationship between the fracture density of coal and lithotype thickness

It is found that there exists certain correlation between the fracture density and lithotype thickness. Most scholars considered that the fracture density was inversely proportional to the lithotype thickness. With the increase of lithotype thickness, the number of fractures decreased (Wang and Chen 1995, Wang *et al*. 1996, Harpalani and Chen 1997, Laubach *et al*. 1998, Zhang *et al*. 2000, Dawson and Esterle 2010). However, Daniels (Daniels *et al*. 1996) found that there was no necessary relationship between the cleat density and lithotype thickness. Previous studies mainly focused on the relationship between the fracture density in the vitrain band and thickness of the band. The relationship of the fracture density of clarain or other coal lithotypes with its thickness was rarely studied. Therefore, there is no relationship between the fracture density and lithotype thickness. In addition, the fracture development is controlled by multiple factors such as coal rank, coal lithotype and its thickness. The influence of other factors should be excluded in the study on the relationship between the fracture density in coal and lithotype thickness. Otherwise, the quantitative and qualitative conclusions obtained would be unreliable.

In this study, some coal samples with low, medium and high coal rank were selected. The fracture densities in vitrain and clarain bands with different thickness were observed (Table 3). The relationship between the fracture density and vitrain/clarain was identified (Figs. 4-6).

The variation rules of fracture density in the coal samples with low coal rank varied with the change of the thickness of vitrain band (Fig. 4). In the DLTK coal sample, the fracture density reached the maximum of 34 per 10 cm when the thickness of band was 3 mm. The fracture density reached the minimum of 12.7 per 10 cm when the thickness of band was 8 mm. The fracture density linearly decreased with the increase of the thickness of vitrain band. The expression is shown as follows

$$Y = -2.486X + 35.33, \qquad R^2 = 0.62 \tag{1}$$

In the Eq. (1), Y stands for the fracture density (/10 cm); X stands for the lithotype thickness (mm).

In the GCK coal sample, when the band thickness was smaller than 20 mm, the fracture density decreased obviously with the increase of thickness. The fracture density showed no obvious change with the increase of band thickness when the thickness was 20-40 mm. The overall trend was that the fracture density had nonlinear decrease with the increase of band thickness. The expression is shown as follows

$$Y = 32.27X^{-0.31}, \qquad R^2 = 0.69 \tag{2}$$

The variation rule of the fracture density in coal samples (Fig. 5) with medium coal rank with the thickness of vitrain band was basically consistent with that under the changing thickness of clarain band when the thickness of band was smaller than 20 mm. Both fracture densities first decreased with the increase of thickness. The difference was that the fracture density in the vitrain band almost did not change with the increase of thickness when the band thickness was greater than 20 mm. The fracture density at this time was about 15 per 10 cm. The expression is shown as follows

$$Y = 65.91X^{-0.55}, \qquad R^2 = 0.89 \tag{3}$$

The fracture density in the clarain band of coal samples with medium coal rank decreased with the increase of band thickness when the thickness of band was smaller than 20 mm. When the band thickness was greater than 20 mm, the fracture density continued to decrease with the increase of band thickness. The expression is shown as follows

$$Y = -4.4\ln(x) + 20.24, \qquad R^2 = 0.38 \tag{4}$$

Table 3 Observation data of the fracture development in different lithotypes with thickness

Coal samples	Coal rank	Coal lithotype	Thickness of band /mm	Density of fractures /10 cm	Coal samples	Coal rank	Coal lithotype	Thickness of band /mm	Density of fractures /10 cm
DLTK	Long flame coal	Vitrain1	2	24.4	PMSK	Fat coal	Clarain1	8	11.1
		Vitrain2	3	34.0			Clarain2	10	9.0
		Vitrain3	6	23.0			Clarain3	10	16.7
		Vitrain4	8	12.7			Clarain4	15	3.3
GCK	Long flame coal	Vitrain1	3	28.0			Clarain5	20	2.0
		Vitrain2	5	15.3			Clarain6	20	5.0
		Vitrain3	5	17.0			Clarain7	20	12.0
		Vitrain4	7	21.0			Clarain8	30	4.0
		Vitrain5	10	16.0			Clarain9	30	4.0
		Vitrain6	20	9.6			Clarain10	30	6.0
		Vitrain7	20	13.5			Clarain11	40	5.0
		Vitrain8	40	11.5			Clarain12	50	2.7
PMSK	Fat coal	Vitrain1	1	66.7			Clarain13	50	6.0
		Vitrain2	2	45.0	WNK	Anthracite	Vitrain1	10	14.0
		Vitrain3	2	60.0			Vitrain2	15	13.0
		Vitrain4	3	34.0			Vitrain3	20	11.0
		Vitrain5	5	16.7			Vitrain4	20	12.0
		Vitrain6	5	30.0			Vitrain5	30	7.0
		Vitrain7	5	37.5			Vitrain6	30	9.0
		Vitrain8	10	12.9			Vitrain7	40	4.4
		Vitrain9	10	16.0			Vitrain8	40	6.6
		Vitrain10	10	17.0			Vitrain9	55	4.0
		Vitrain11	20	10.8			Vitrain10	65	5.8
		Vitrain12	25	13.1			Clarain1	10	12.0
		Vitrain13	30	8.0			Clarain2	10	13.0
		Vitrain14	30	8.5			Clarain3	10	14.0
		Vitrain15	30	11.0			Clarain4	20	10.0
		Vitrain16	30	11.5			Clarain5	20	11.0
		Vitrain17	30	12.3			Clarain6	30	7.0
		Vitrain18	30	12.7			Clarain7	40	4.0

There was significant difference between the variation rule of the fracture density in coal samples (Fig. 6) with high coal rank with the changing thickness of vitrain band and the variation of the fracture density with the changing thickness of clarain band. In vitrain band, the fracture density decreased with the increase of band thickness, from the maximum of 13 per 10 cm to the minimum of 4 per 10 cm. The expression is shown as follows

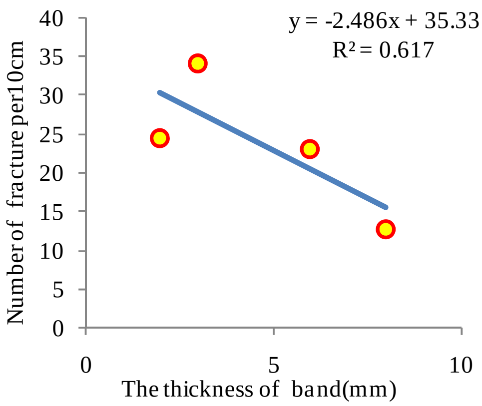
$$Y = 79.71X^{-0.69}, \qquad R^2 = 0.81 \tag{5}$$

The fracture density in the clarain band of coal samples with high coal rank had a good linear relationship with the band thickness. The fracture density decreased linearly with the increase of band thickness. The expression is shown as follows

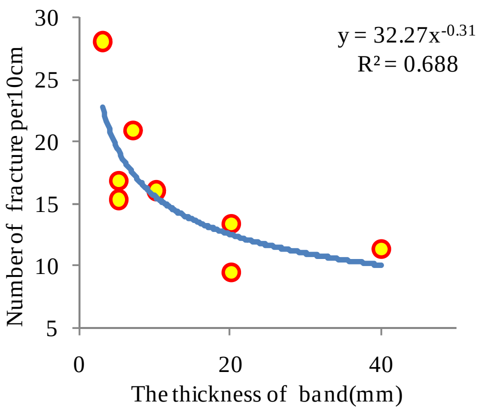
$$Y = -0.3X + 16.14, \qquad R^2 = 0.96 \tag{6}$$

The following conclusions are drawn through the above statistical results: (1) The overall variation rule of fracture density in coal with the band thickness varies from one lithotype to another. There are at least 3 variation patterns, linear decrease, nonlinear decrease, and first decrease and then remaining unchanged; (2) The macerals and structure of coal are complex and disorderly. This results in several variation patterns of fracture density with the change of band thickness. However, the general trend is that the fracture density in coal decreases with the increase of band thickness; (3) The development rules of fractures are different for the same lithotype with different thickness in the coal samples with the same coal rank. (4) In the coal samples with the same coal rank, the fracture density may vary in the vitrain and clarain bands with the changing band thickness.

The compositions and pore structures of bands with different thickness are not completely identical. Therefore, the hydrocarbon generating potential and fluid preservation ability vary between the bands. As a result, the volume of accumulated gas and fluid pressure generation are different, resulting in a diversity of variation trends for the fracture density. On the whole, the strength of coal body will increase and the fluid pressure necessary for the coal body destruction will be higher with the increase of band thickness. The fluid within a larger range is required to converge to provide sufficiently higher fluid pressure. The band with greater thickness is more strongly affected by in-situ stress. As a result, the accumulated fluids break through the coal body under the dual action of fluid pressure and in-situ stress. Thus, the fractures with large spacing are formed. The rupture of the band with smaller thickness requires lower fluid pressure. The fluid

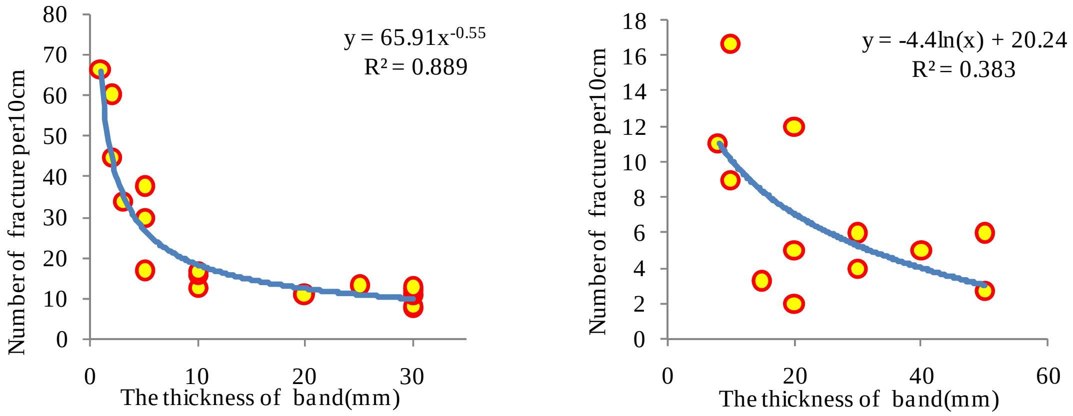


(a)



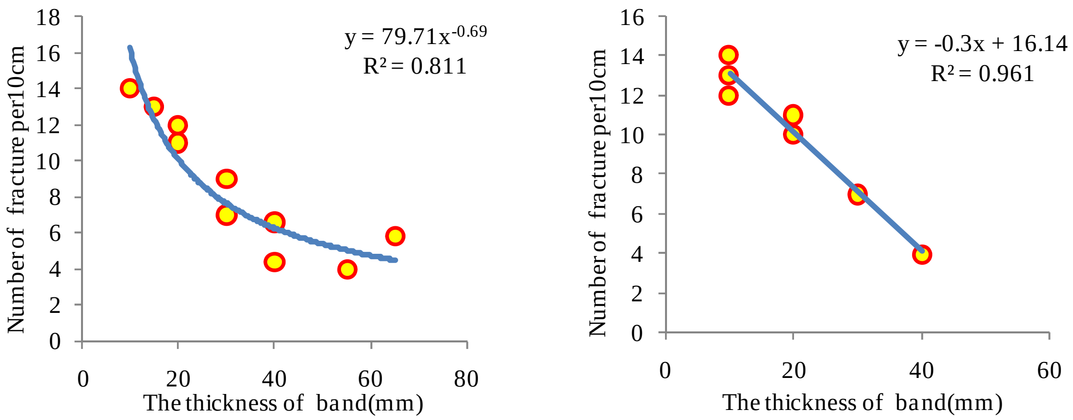
(b)

Fig. 4 Relationship of the fracture densities in long flame coal and gas coal with the thickness of vitrain band: (a)DLTK; (b)GCK



(a) (b)

Fig. 5 Relationship between the fracture density in coking coal (PMSK) and thickness of the vitrain/clarain band: (a) vitrain band; (b) clarain band



(a) (b)

Fig. 6 Relationship between the fracture density in anthracite (WNK) and thickness of the vitrain/ clarain band: (a) vitrain band; (b) clarain band

pressure and volume sufficient to produce the fractures are small. The fluids produced by coal matrix within the small range can provide sufficient fluid pressure to break through the band. Relatively concentrated fractures will be generated within a short distance (Wang *et al*. 1996). This is the reason for the difference in variation pattern of fracture density with the band thickness. But generally, the fracture density in thicker bands is smaller than that with thinner bands.

4. Conclusions

Coal properties, band thickness and fracture density date of selected mine coals from typical coal ming areas in Inner Mongolia, Shanxi, Hebei and Henan have been investigated in this study. Fracture development varies within the different coal lithotypes. For the same thickness of coal, the fracture densities for different lithotypes of coal samples with low, medium and high coal rank follow a consistent variation rule in the direction perpendicular to the bedding plane: vitrain > clarain > durain. There is no fracture development in fusain. The study on the development characteristics of fracture for different lithotypes is crucial for the prediction of reservoir permeability and division of superior coalbed methane blocks.

The overall variation rule of fracture density in coal with the band thickness varies from one lithotype to another. There are three variation patterns of the fracture density with the thickness of vitrain band of coal samples with the same coal rank: linear decrease, nonlinear decrease, and first decrease then remaining unchanged. There are two variation patterns of the fracture density with the thickness of clarain band in the coal sample with the same coal rank: linear decrease, and nonlinear decrease. For the same coal rank and coal lithotype, the fracture density generally decreases with increasing bands thickness. If this finding is extended to the coal seams for coalbed methane reservoir studies, it would be useful for providing an indicator for coalbed permeability and coalbed methane producibility.

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