

Mechanical deterioration and thermal deformations of high-temperature-treated coal with evaluations by EMR

Biao Kong^{1,2,3}, Sixiang Zhu¹, Wenrui Zhang^{*1,2}, Xiaolei Sun¹, Wei Lu^{1,2} and Yankun Ma^{**2}

¹College of Safety and Environmental Engineering, Shandong University of Science and Technology, Qingdao 266590, China

²Engineering Technology Research Centre for Safe and Efficient Coal Mining (Anhui University of Science and Technology), Huainan, 232001, China

³State Key Laboratory of Coal Mine Safety Technology, China Coal Technology & Engineering Group Shenyang Research Institute, Shenyang, 113122, China

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Abstract. With the increasing amount of resources required by the society development, mining operations go deeper, which raises the requirements of studying the effects of temperature on the physical and mechanical properties of coal and adjacent rock. For now, these effects are yet to be fully revealed. In this paper, a mechanical-electromagnetic radiation (EMR) test system was established to understand the mechanical deterioration characteristics of coal by the effect of thermal treatment and its deformation and fracture characteristics under thermo-mechanical coupling conditions. The mechanical properties of high-temperature-treated coal were analyzed and recorded, based on which, reasons of coal mechanical deterioration as well as the damage parameters were obtained. Changes of the EMR time series under unconstrained conditions were further analyzed before characteristics of EMR signals under different damage conditions were obtained. The evolution process of thermal damage and deformation of coal was then analyzed through the frequency spectrum of EMR. In the end, based on the time-frequency variation characteristics of EMR, a method of determining combustion zones within the underground gasification area and combustion zones' stability level was proposed.

Keywords: coal; EMR; mechanical deterioration; stability evaluation; temperature

1. Introduction

As mining operations go deeper, the effect of high ground temperature on the physical and mechanical properties of coal and adjacent rock can be found obviously. The failure behaviors of coal and adjacent rock in deep mining areas are quite different from that of shallow areas (Feng *et al.* 2018, Yang *et al.* 2019, Wang *et al.* 2020). Consequently, it is essential to understand the mechanism of deformation and mechanical strength of coal and rock by thermal-mechanical coupling effect because this is the basis for determining underground coal gasification area (Xin *et al.* 2019), studying the topic of safe mining in deep coal mines (Kong *et al.* 2019a, Yu *et al.* 2020), and evaluating thermal stability of underground coal and adjacent rock after combustions happened underground (Chen *et al.* 2020, Du *et al.* 2020, Li *et al.* 2020, Liu *et al.* 2020, Qi *et al.* 2020).

The physical characteristics of high-temperature-treated coal and rock have been studied well, which mainly include research of mechanical parameters, deformation and fracture characteristics, and the constitutive models (Tian *et al.* 2012, Kong *et al.* 2016, Zhang *et al.* 2020, Sirdesai *et al.* 2018, Hu *et al.* 2020). Feng analyzed the relationship

between parameters in the rock constitutive model at high temperature and normal temperature (Feng *et al.* 2020). Based on the constitutive model of rock at normal temperature, a constitutive model reflecting the effect of high temperature was established. The rock of different lithology has obvious damage change after temperature change. The macroscopic mechanical properties of rock after thermal damage are mainly characterized by deformation. (Kong *et al.* 2018a,b,c, Sun *et al.* 2019). Sharma used a variety of advanced technologies to test and analyze the damage of coal and rock mass, and calculated the relationship of damage factors by means of data analysis, such as neural network and fuzzy mathematics (Sirdesai *et al.* 2013). The rule of thermal damage on coal pore structure and free radicals by using automatic specific surface area analyzer and electron spin resonance spectrometer was studied, revealed the internal mechanism of thermal damage on coal structure and natural oxidation characteristics, and provided a basis for the prevention and control of thermal damage affecting coal spontaneous combustion (Shao *et al.* 2022). The above are all tests and studies on the mechanical properties of coal after temperature treatment. However, it should be noted that, in fact, during the process of thermal damage, coal and rock are often under coupled conditions of temperature and pressure. (Feng *et al.* 2018, Barton.2020). Thus, studying the mechanical behavior and deformation and fracture characteristics of coal and rock by considering both temperature and pressure conditions can give us a better idea of what would happen in the field.

*Corresponding author, Professor
E-mail: wenrui.mao@163.com

**Corresponding author, Professor
E-mail: ykma@aust.edu.cn

There are some researchers who work on the mechanical properties and fracture characteristics of coal and rock under the effect of both temperature and pressure. The mechanical properties of coal and rock after high-temperature and immersion treatment through was tested, both high-temperature method and immersion method will cause mechanical damage to coal and rock (Gao *et al.* 2022, Kong *et al.* 2021). It revealed the effect of temperature on coal's internal structure. It is found that the micro deformation and fracture of rock mass will change in stages after the rock is treated by temperature, and 300°C is a relatively obvious stage change temperature point. (Yu *et al.* 2017).

The effect of the temperature can cause physical and chemical changes in coal and rock structure, also lead to the vaporization of water inside and oxidation of coal and rock. That would affect the formation and distribution of temperature field inside coal and rock, thus influencing the thermal stress produced, ultimately leading to the variations of coal fracture development (Zhang *et al.* 2019, Molaro *et al.* 2017). At present, acoustic emission (AE) and EMR are effective monitoring methods for characterizing the deformation and failure of coal and rock (Kong *et al.* 2019a, Kong *et al.* 2019b, Kim *et al.* 2020, Zhang *et al.* 2018). Through AE testing of high-temperature granite, the changes of acoustic emission parameters under heating conditions are evaluated and compared (Cai *et al.* 2022). At present, there are a lot of researches on AE and EMR in the process of coal and rock failure under load as well as under the action of continuous heating and the whole process of coal and rock thermal deformation (Li *et al.* 2019, Song *et al.* 2019). On the one hand, the coal body is heated, heated, deformed and cracked to generate free charges, and EMR is generated for the dipole transient and hot electron transition to cause the free electrons to move at variable speeds, on the other hand, the coal combustion flame generates charged ions, which generate EMR in the chain reaction process of generation and disappearance of charged ions (Kong *et al.* 2019c). The reasons for the mechanical degradation of sandstone after high-temperature treatment were analyzed (Liu *et al.* 2020, Zhang *et al.* 2022). The impact of temperature change on the internal composition of sandstone, especially the reduction of SiO₂ content and the increase of porosity, is the main reason for the mechanical degradation.

In the process of underground coal mining and coal gasification, the deformation and rupture characteristics of coal considering the effect of temperature are becoming a critical issue to be understood, but none of the existing methods can directly characterize the thermal deformation and fracture characteristics of coal. Also, existing experimental designs are more focusing on single parameter and do not reflect the coal deformation and fracture under different conditions.

EMR technique has the advantage of multi-direction cross-locating and has been widely used to monitor and provide early warnings for rock dynamic deformation and failure. Therefore, in order to study the mechanical deterioration characteristics of coal under the action of temperature-loading and the deformation and fracture

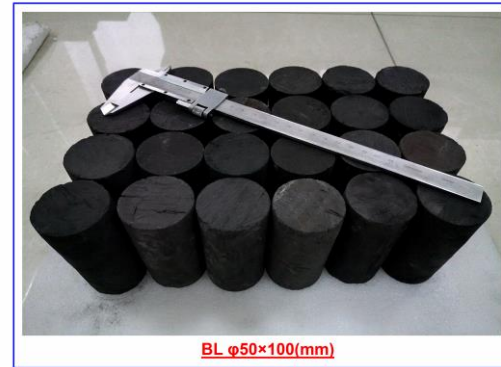


Fig. 1 Coal samples in the shape of cylinder

characteristics of coal body in the process of thermal treatment, in this paper, change of coal's mechanical properties under the effect of temperature was studied, and the deterioration of mechanical strength of coal was analyzed. In addition, EMR technology was used to characterize the deformation of coal. Deformations under different levels of heating damage were recorded and concluded. The research results can then be further applied to guide deep underground coal mining and can also be used to evaluate the underground situations of coal gasification.

2. Experimental method

2.1 Preparation and analysis of coal samples

The selection of coal samples is very important for the research results. In order to analyze the mechanical deterioration characteristics of coal after temperature treatment and the change characteristics of EMR, this paper first selects a bituminous coal that has more occurrences on the earth for research. Twenty-four coal samples (as shown in Fig. 1) used in the experiment were processed by method of drilling core sampling from bulk coal taken from BaiLu mine (B1), Shuozhou, Shanxi. Samples were shaped in cylinder of $\Phi 50\text{ mm} \times 100\text{ mm}$. The test sample is taken out by the special coal core sampling equipment of China University of mining and technology. After taking out the coal sample, the surface flatness shall be checked first, and the samples with cracks on the surface shall be removed. Secondly, the surface smoothness of the selected samples is treated to prevent the end effect during the thermal damage test, which will affect the experimental results.

The proximate analysis of the selected coal samples were carried out and the spontaneous combustion (SponCom) tendency of the coal samples was also tested and recorded based on China's national standard as shown in Table 1.

2.2 Experimental system and procedures

The mechanical-acoustic-electric experiment system is shown in Fig. 2. This system is capable of testing the thermal

Table 1 Proximate analysis and spontaneous combustion tendency index

Coal	Types of coal	Mad (%)	Vad (%)	Fcad (%)	Aad (%)	SponCom tendency
BL	Long flame	3.72	26.42	59.75	24.56	II

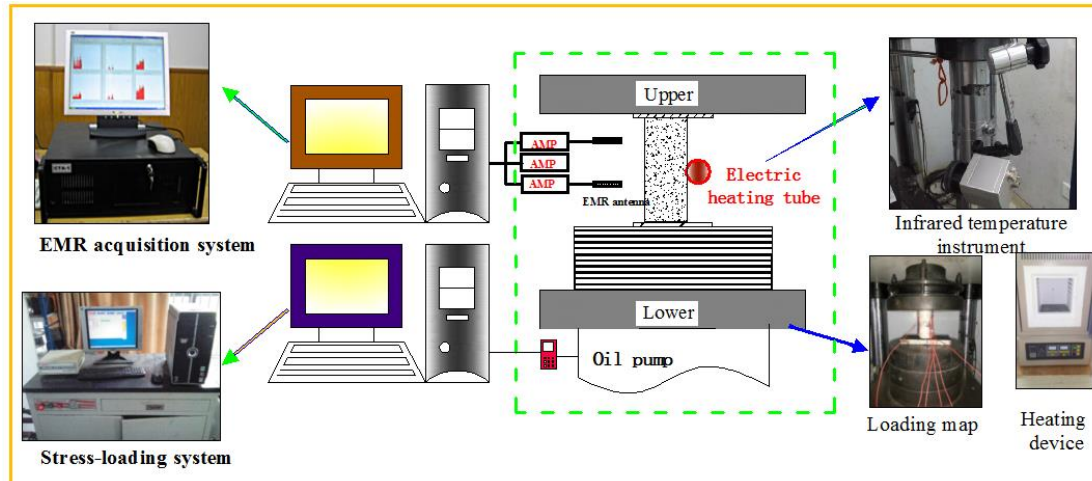


Fig. 2 Experimental system diagram

damage under temperature-pressure coupling conditions. It can be seen from the figure that the system mainly consists of heating treatment device, loading destruction device, EMR signal testing and receiving system, etc.

(1) Experimental steps

1) Because the experiment needs to carry out EMR test under different conditions, such as coal heating, coal uniaxial loading failure, heating and loading coupling damage. Before the EMR test of uniaxial loading failure, the coal body should be heat treated first. Pre-treat temperature including normal temperature (25°C), 50°C, 100°C, 200°C and 300°C. According to the existing heat treatment process, the coal body needs to keep constant temperature for 2 hours after heat treatment, and then the experiment is started after the coal body is cooled naturally.

The micro damage fracture of coal and rock occurs after heat treatment. The wave velocity is measured by wave velocity tester to reflect the change of coal damage. In the process of experiment, the wave velocity tester is also used to test the wave velocity of coal, and the samples with large difference of wave velocity are removed. Scanning Electron Microscope (SEM) was also used for analyzing the microstructure characteristics of the high-temperature-treated coal in this step.

2) Construct the EMR system for testing thermal damages under the coupling effect of temperature and pressure. Pressure loading rate was 50N/s. The threshold value of EMR acquisition system and acquisition rate were adjusted to ensure the consistency of the testing system. Magnification of the EMR acquisition system was 60dB and the threshold value range was 45-55dB. Acquisition rate was 1MSPS. After all settings, coal samples were tested for their mechanical behavior and EMR variations in a shield room.

3) A DC electric heating tube was fixed in the middle of the coal samples to test the EMR change of coal samples under the effect of continuous heating. Change of the temperature field covering entire sample was collected in real time by an infrared imager.

4) Adjust the threshold value and the acquisition frequency of the EMR collection to let the magnification of the EMR acquisition system 40dB, and the acquisition rate at 1MSPS. While strictly controlling the consistency of testing parameters, patterns of coal's mechanical-electric dynamics under the coupling effect of temperature and pressure variations were concluded. Analyze and process the experimental data.

3. Mechanical deterioration of coal after high temperature treatment

Coal samples' micromorphology characteristics were analyzed based on the SEM observations. As shown in Fig. 3, the development of cracks varies along with the levels of temperature used to treat the coal samples.

At the level of normal temperature (25°C), the fracture surface is relatively smooth, and there are few defects on the surface. With 50°C treatment, the micro defects on the surface have some slight evolution. When it comes to 100°C treatment, new micro defects are found on the surface. Considering the 200°C treatment, the micro defects evolve further in the coal body and new micro cracks can be found clearly, as at 200°C, water is further promoted to evaporate, and the mineral particles are also inflated because of the heat. When the thermal expansion deformation is greater than the internal cementation force, thermal damage/cracking is formed. When thermal treatment reaches 300°C, thermal

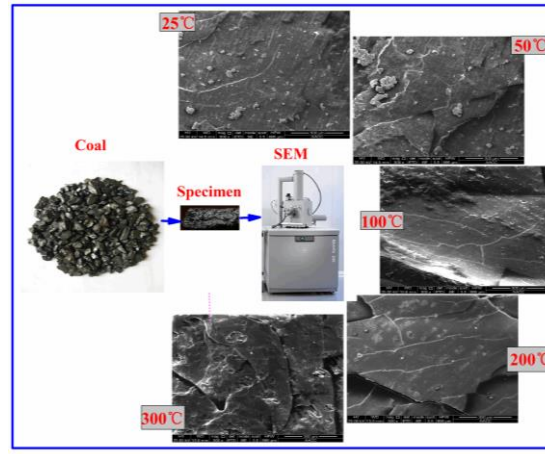


Fig. 3 Coal samples' micromorphology

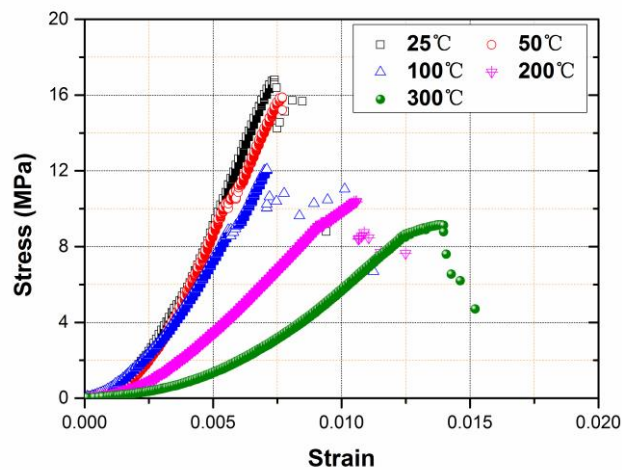


Fig. 4 Stress-strain curves

damage is intensified and the micro defects in the coal body expand. The accumulation of micro defects lead to micro cracks that can be clearly seen from the surface.

3.1 Changes in mechanical properties

The stress-strain curves, peak strength and elasticity modulus of temperature-treated coal samples are shown in Figs. 4 and 5. The formula used to calculate the change rate is: $C_T = (R_{T_0} - R_T) / R_{T_0}$. The calculation formula of the relative reduction is: $\Delta C_T = (R_{T-1} - R_T) / R_{T-1}$.

As shown in Figs. 4 and 5, the mechanical properties of coal are affected largely by high-temperature treatment. The peak strength of coal is 16.81MPa at normal temperature compared to only 9.16 MPa after treatment at 300°C. There is in total 45.5% decrease between this two numbers. It is the thermal damage, loss of water inside the coal, and coal structure change caused by high temperature that reduce the strength of coal.

The strain is also affected by temperature treatment. It is 0.0094 at normal temperature, while this number increases

to 0.0156 after treatment at 300°C. That is because, as temperature rises, the ductility of coal body increases leading to the increase in peak strain.

3.2 EMR characteristics

Changes in EMR characteristics are shown in Fig. 6.

As shown in Fig. 6, the EMR signals can be generated by the deformation and failure of the coal, as the mechanical properties of coal are reduced after high-temperature treatment, the temperature will cause thermal damage to the coal body, the internal moisture of the coal body will be lost, the internal structure of the coal body will change, and its mechanical strength will decrease, leading to the change of EMR measurement value, and the EMR signals amplify with the increase of the stress. The EMR signals are not continuous, but paroxysmal. Compared with coal samples that were treated under normal temperature, other coal samples treated with higher levels of temperature showed significant differences regarding the EMR signals.

With the increase of temperature, the ductility and peak

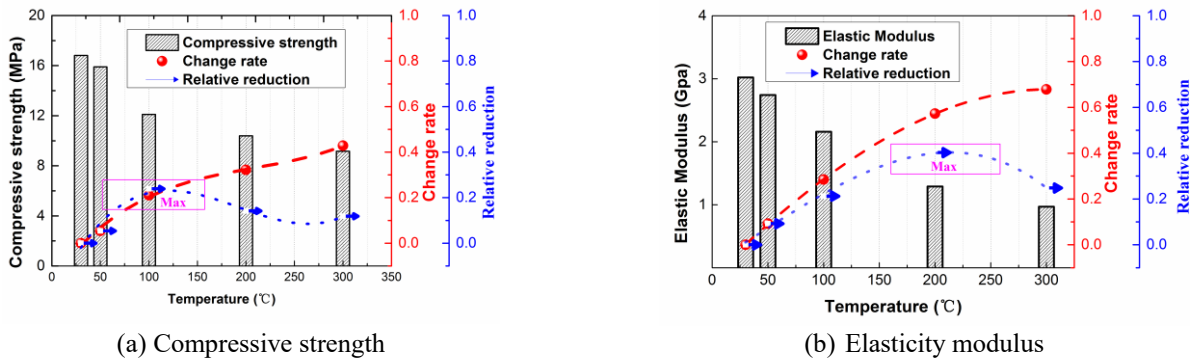


Fig. 5 Changes in mechanical parameters

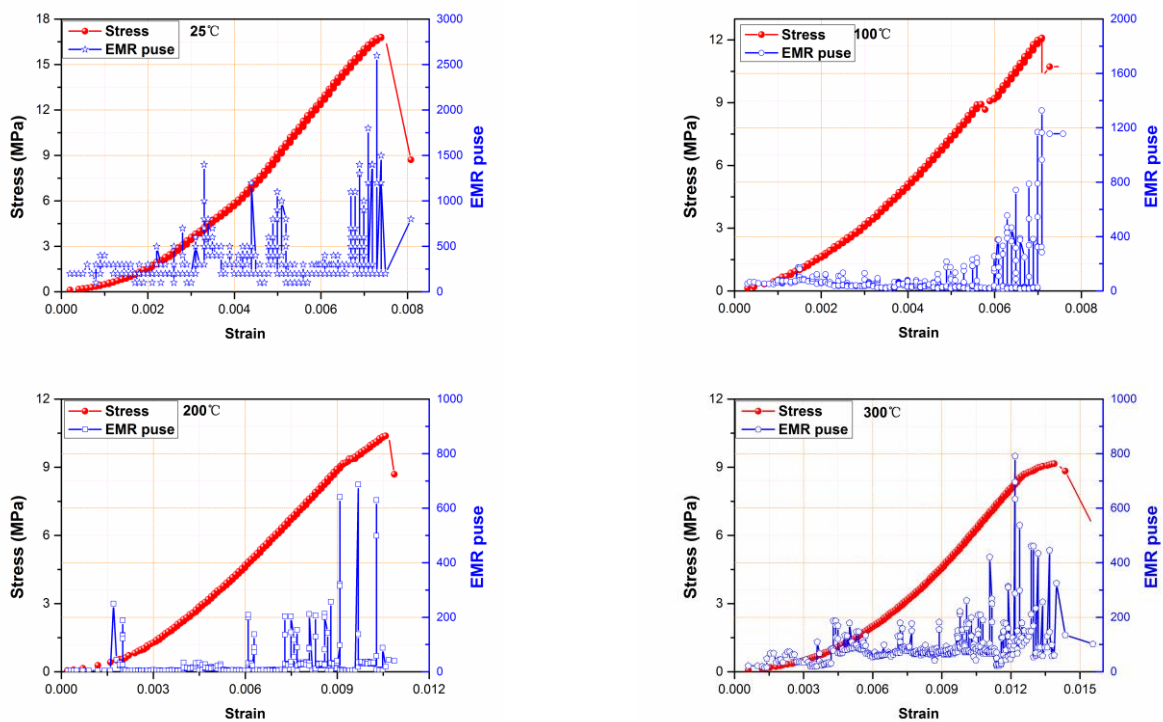


Fig. 6 EMR curves of coal under different temperature levels of treatment

strain of coal increase; After treatment at different temperatures, the deformation and destruction of coal body will produce EMR, the value of EMR also changes with temperature rise.

4. EMR characteristics of coal's thermal damage

4.1 EMR test results of coal under unrestrained heating condition

The EMR test results of coal under unrestrained heating conditions are shown in Fig. 7.

As shown in Fig. 7, during the heating process, coal can produce clear EMR signals, and as early as the initial stage of heating (50°C), there was weak EMR signals detected. As the temperature rises, the EMR strength increases

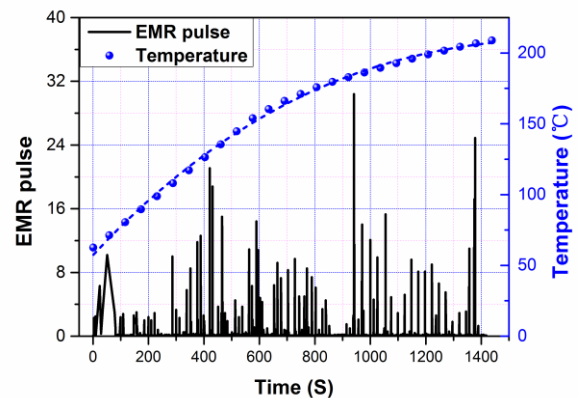


Fig. 7 EMR signals of coal in unrestrained heating conditions

gradually. Thus, we can conclude that high temperature can lead to thermal damage of coal, and under different levels of temperature, the strength of EMR signals produced from coal varies.

4.2 EMR test results of coal under uniaxial compression condition

The test results of the EMR of coal under uniaxial compression condition are shown in Fig. 8.

In the process of uniaxial compression test, the EMR signals increase gradually with the increase of stress, and the most significant EMR signal can be found at the moment when the coal body is unstable and destroyed.

Comparing Figs. 7 and 8, there are some differences in the two curves. From the EMR time series characteristic analysis, EMR signal change is richer in the process of temperature increase (Fig. 7), because during the heating process of coal and rock, under the action of temperature, the internal particles of coal and rock deform and expand to produce initial fracture, which can produce obvious electromagnetic pulse signal at the beginning of heating. The temperature increases the ductility of coal and rock, and the EMR signal gradually increases. In the process of uniaxial compression, brittle failure mainly occurs when the coal and rock are unstable and fractured, and the EMR signal suddenly changes, the change rule of electromagnetic pulse signal is obvious only when the coal and rock are unstable and destroyed, which can also explain the observations of EMR signals in the initial stage of heating.

4.3 EMR test results of coal under coupled temperature-pressure condition

Under the condition of temperature-pressure coupling, the EMR test results of coal damage and destruction are shown in Fig. 9.

Under the conditions of temperature-pressure coupling, the change of EMR is significant. When the initial heating process and stress-loading starts, the damage of coal produces obvious EMR signals, and the value is high. With the temperature and the pressure gradually increasing, EMR signals change a lot. When coal body is unstable and

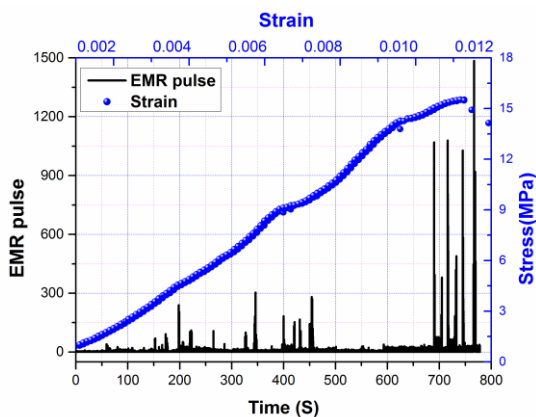


Fig. 8 EMR signals of coal under uniaxial compression

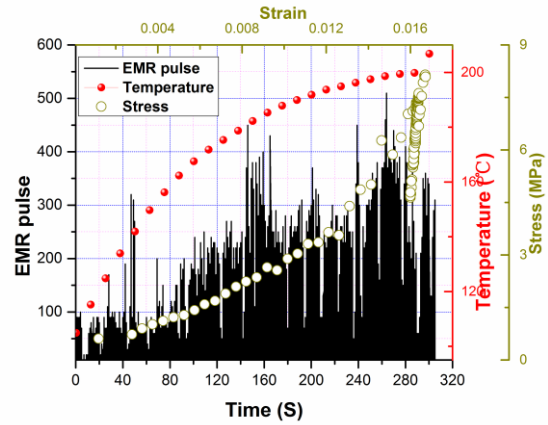


Fig. 9 EMR signals of coal under temperature-pressure coupling condition

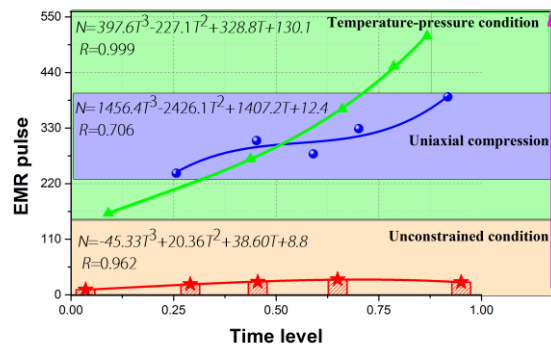


Fig. 10 EMR changes at different time levels under three damage conditions

destroyed, the EMR signal reaches the maximum, and there is a sudden increase in the signal at the failure stage. That is, under the condition of temperature-pressure coupling, EMR signals are stronger compared with single-parameter testing owing to more severe damage of coal.

4.4 Analysis of EMR curves under different conditions

By analyzing the EMR curves under different conditions, Tables 2 and 3 are concluded.

Note: the temperature is the apparent temperature measured by the infrared

From the Tables 2 and 3, the changes of the EMR signal in different damage (temperature and loading) phases differ. The different response of the EMR signal indicates various degrees of damage and rupture state. This further illustrates that the EMR signal can be used to characterize the thermal damage process of the coal body. EMR variations under three different conditions are shown in Fig. 10.

According to the Fig. 10, following can be concluded.

(1) At different temperature stages, the difference of EMR values are obvious. (2) The EMR signals of coal under the conditions of temperature-pressure coupling are much higher than those under unconstrained heating conditions. This is because the coal samples were damaged more heavily by the coupling of temperature-pressure effect.

Table 2 Change characteristics of EMR in coal heating and temperature-pressure coupling

Number	Temperature stages	Unconstrained heating condition – Single parameter - temperature	Temperature-pressure coupling
1	0~70°C	EMR signal generation, relatively weak	EMR Signal is higher than unconstrained heating condition
2	70~120°C	EMR signal increasing and the change is obvious	Enhanced change, high EMR signal intensity
3	120~170°C	EMR signals growth rate slows down	EMR signal is increasing, and it is more obvious
4	170°C~	EMR signal fluctuation change	The speed of EMR signal enlargement is obvious

Table 3 Change characteristics of EMR in coal heating and loading process

Number	Loading stage	Uniaxial loading at normal temperature – single parameter – pressure	Temperature-pressure coupling
1	Initial loading	Signal generation, relatively weak	The obvious signal is produced, higher than the normal temperature
2	Compaction stage	Fluctuation and low measurement	Enhanced change, high signal intensity
3	Elastic phase	Fluctuation change	The signal is increasing, and it is more obvious
4	Instability rupture	Signal mutation change	The speed of signal enlargement is remarkable

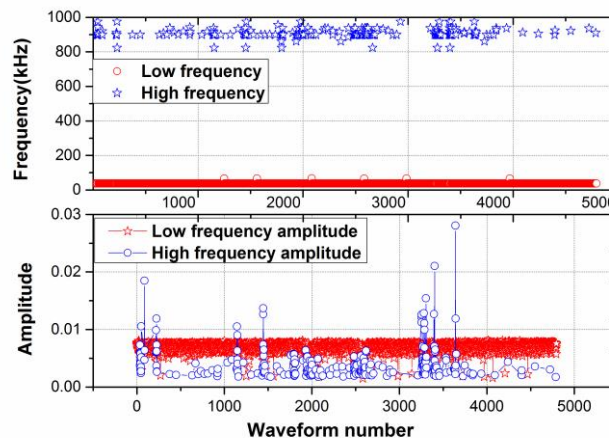


Fig. 11 EMR main frequency amplitude of coal under unrestrained heating condition

(3) Under the condition of temperature-pressure coupling, the EMR signals are more detectable. In the process of uniaxial compression, the EMR signal strength increases gradually, and only show significant signal when coal body is unstable and destroyed, while under the condition of temperature-pressure coupling, the EMR signal can be found obviously along the whole loading process.

4.5 EMR spectrum characteristics of coal under different damage conditions

The curves of the main frequency amplitude of EMR under unrestrained heating condition are shown in Fig. 11.

The main frequency of EMR changes with the temperature change, and the main frequency of EMR also changes obviously at low frequency 0~50 KHz and high frequency 800~1000 KHz during the heating process of

coal. The amplitude of EMR changes gradually during the process of coal heating, and the larger the amplitude, the greater the degree of particle destruction it represents. The amplitude of the EMR fluctuates during the heating process of coal within the range of 0~0.025 and the change of the high frequency amplitude is obvious while low frequency amplitude maintains at a certain value. It indicates that EMR signals fluctuate sharply during the initial heating process, while at later stages, although the EMR value is higher, amplitude is lower.

The changes of the main frequency amplitude of the EMR under the condition of temperature-pressure coupling are shown in Fig. 12.

In the process of temperature-pressure coupling, the main frequency of EMR is within 850~950KHz, and there is no low frequency EMR signals. The amplitude change is obvious and it gradually increases as well. The change of

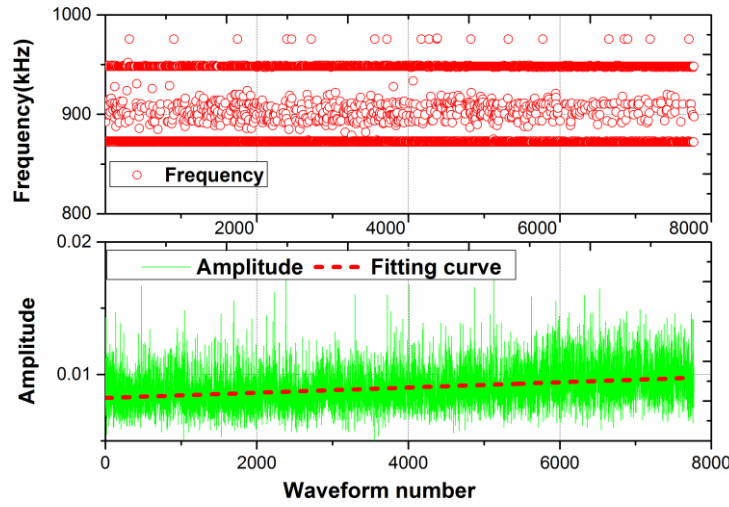


Fig. 12 EMR main frequency amplitude of coal under temperature and pressure condition

main frequency amplitude of EMR under the condition of temperature-pressure coupling indicates that the fracture damage is aggravated under the condition of temperature-pressure coupling. Number of cracks and defects increase, and the deformation and fracture of coal is more serious than that of single-parameter damage.

5. Discussion

5.1 Mechanical deterioration of high-temperature-heated coal

Coal is a heterogeneous porous medium with different pore sizes. When the coal body is heated and heated, the internal structure of coal will undergo different degrees of thermal deformation and thermal expansion. Due to the different thermal expansion and deformation tolerance of each component, different degree of thermal cracking will occur. Thermal stress is formed in coal body due to deformation and extrusion of thermal expansion, which further causes thermal deformation and cracking of coal body. The coupling relationship between thermal stress and temperature is obtained by experimental statistics (Xiao *et al.* 2016)

$$\sigma_T = (T_2 - T_1) / KEA \quad (1)$$

Furthermore, according to the theory of material mechanics and damage mechanics, the thermal stress of coal and rock materials has a certain relationship with its own physical dilation and deformation of particles, as shown in formula (2) (Xi *et al.* 2009)

$$\sigma_T = (A_2 - A_1) \Delta T \frac{E_1 E_2}{(E_1 + E_2)} \quad (2)$$

The fracture and propagation analysis of coal and rock failure crack, based on this, the relationship between crack growth and fracture stress can be used (Song *et al.* 2016)

$$\sigma_{cT} = \frac{2^{\frac{1}{4}} K_{IC} \sqrt{3\pi h}}{8\xi^{\frac{1}{2}} \theta_0} \quad (3)$$

It is found that there is a certain relationship between the temperature of coal and rock and the elastic modulus of coal and rock itself. Basically, with the increase of temperature, the elastic modulus of coal and rock decreases gradually. However, the above corresponding relationship can not fully reflect the relationship between the elastic modulus of coal and rock and temperature. Here we define the elastic modulus as a function of temperature

$$E_T \approx Af(t, x) \quad (4)$$

After the coal body is treated at different temperatures, the change of elastic modulus of coal under load is fitted

$$E_T = 2E - 05T^2 - 0.015T + 3.411 \quad (5)$$

According to the above formula, we can get the fitting relationship of elastic modulus of coal under loading failure after different temperatures. From the formula, it can be seen that the higher the temperature treatment, the smaller the elastic modulus of coal under load. According to the research, we assume that the yield of thermal damage of coal is a function of elastic modulus, which is expressed by the following formula

$$D(T) = 1 - \frac{E_T}{E_0} \quad (6)$$

Based on the above analysis, we established the thermal damage at different temperatures, ss presented in Fig. 13. The thermal damage parameter obtained from Fig. 13 increases with rise in temperature. The coal body is subjected to heat treatment at 300°C, and the degree of thermal damage is high. When the temperature continues to rise, the strength of coal body will continue to decrease under the influence of temperature.

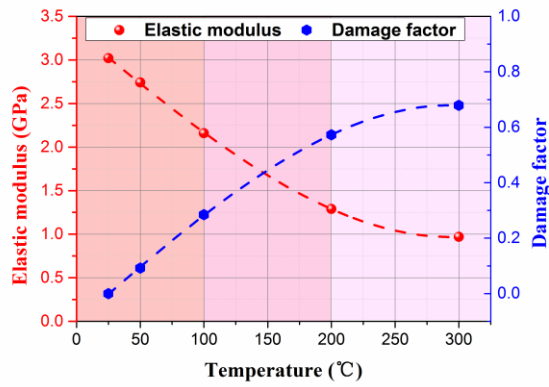


Fig. 13 Changes in the damage factor

5.2 Analysis of the EMR generation

Due to the different pore fracture characteristics of coal with different metamorphic degrees, the change rules of EMR signals at different positions during the heating process will be different, but the overall change trend of EMR signals of different grades of coal is consistent. The scholars have studied the mechanism of EMR produced by coal and rock mass fracture under load. One of the points has been verified is that the irregular migration of free electrons produced by coal and rock mass under load can change electromagnetic field and further generate EMR. The changes of electric and magnetic fields produced by free electron charged q transport are shown in the following formula (He *et al.* 2011, Wang *et al.* 2011, Wang *et al.* 2003)

$$\begin{cases} E = \frac{er}{4\pi\epsilon_0 r^3} + \frac{e}{4\pi\tau_0 c^2 r^3} r \times (r \times v) \\ B = \frac{ev \times r}{4\pi\epsilon_0 c^3 r^3} + \frac{ev \times r}{4\pi\tau_0 c^2 r^3} \end{cases} \quad (7)$$

$$\begin{aligned} \vec{E} &= (1 - (i^2 v^2 / c^2)) \frac{e\vec{r}}{4\pi\epsilon_0 [(1 - (i^2 v^2 / c^2))r^2 + (i\vec{v} \cdot \vec{r} / c)^2]^{3/2}} + \frac{i^2 e}{4\pi\epsilon_0 c^2 r} \vec{i} \times [\vec{i} - (i\vec{v} / c) \times \vec{a}] \\ &= \vec{E}_1 + \vec{E}_2 \\ \vec{B} &= (1 - (i^2 v^2 / c^2)) \epsilon_0 \frac{e i^2 \vec{a} \times \vec{r}}{4\pi\epsilon_0 c^2 [(1 - (i^2 v^2 / c^2))r^2 + (i\vec{v} \cdot \vec{r} / c)^2]^{3/2}} + \frac{i^2 e}{4\pi\epsilon_0 c^3 r} \vec{v} \times [\vec{i} - (i\vec{v} / c)] \\ &= \vec{B}_1 + \vec{B}_2 \end{aligned} \quad (8)$$

where, E and B represent the electric field and magnetic field produced by the electronic motion respectively. C ; v is the velocity vector of charged particles, m/s; R is the distance from the distance of charged particles to the center point; the dielectric constant of the coal and rock materials in the vacuum is characterized. i is the refractive index of the coal and rock medium; ϵ_x is the dielectric constant of the medium; \vec{a} is the acceleration of the electron; \vec{n} is the unit normal vector; $\{\vec{E}_1, \vec{B}_1\}$ is related to the Coulomb electric field and the magnetic field, and the $\{\vec{E}_2, \vec{B}_2\}$ is related to the emission field and the magnetic field.

According the formula (7) and (8), the generation of EMR from thermal damage of coal is directly related to the accumulation of free charge and the change of electron acceleration.

When the coal body is damaged by heat, its internal structure is weakened, and two kinds of obvious electromagnetic field sources will be produced. One is that the thermal damage of coal is irreversible when it is loaded and launched, and then the electronic balance of coal body is broken by external load. There are obvious electron aggregation and emission, forming electromagnetic field. If the load is sustained, the electrons in the coal continue to gather, and the internal balance is further broken, resulting in the uneven change of electron velocity. The inhomogeneous change of electron velocity further forms EMR source.

5.3 Analysis on the variation law of EMR of coal with different metamorphic degrees

In this paper, long flame coal is selected for research. The main purpose is to explore the laws and differences of EMR signals generated at different temperature stages in the process of coal heating, reveal the generation mechanism of EMR in the process of coal heating, and provide a theoretical basis for the inversion of temperature by EMR signals and the realization of efficient early warning of coal spontaneous combustion. Based on this, this study selects the long-flame coal in Bailu Mine, Shuozhou, Shanxi Province as the test object, and obtains the change law of EMR signal at different temperature stages during the coal heating process. First of all, a large-scale coal spontaneous combustion simulation experiment platform was established, which is closer to the coal spontaneous combustion environment. Through the experiment, it was proved that the EMR signal can be generated during the coal heating process, and the change rule of the EMR signal time series and spectrum characteristics was analyzed. Finally, the generation mechanism of EMR in the coal spontaneous combustion process was revealed.

Previously, an EMR testing system for coal heating was established to study the change law of EMR of coal with different metamorphic degrees in the heating process (Kong *et al.* 2018b, Kong *et al.* 2019c, Kong *et al.* 2021). Through experiments, the EMR signals of long flame coal, gas fat coal and coking coal in the heating process were tested, synchronously tested the temperature values at different locations, and selected EMR waveforms at different temperature stages for analysis, It shows that the internal deformation and fracture of coal heating is also a process of gradual development and evolution. According to the time sequence change characteristics of EMR signals in the process of coal heating and heating, it is analyzed that there will be differences in the change laws of EMR signals at different positions of three kinds of coal during the heating process, and the differences in the intensity of EMR are also large, but the overall change trend of EMR signals is consistent.

The experimental results show that the EMR signal of long flame coal increases gradually with the increase of time, but the EMR energy value is greater than the signal strength of coking coal and gas fat coal, and the EMR signal of coking coal increases gradually, but the signal change of long flame coal and gas fat coal is obvious after the coking coal heats up for 500s. At the initial heating stage of coal, the measured value of EMR is relatively small. With the increase of heating time, the EMR gradually increases. The results show that the change trend of EMR energy and pulse number of coals with

different metamorphic degrees is similar as a whole, and they all show a gradually increasing trend with the increase of time.

Based on the EMR test of coal in the heating process, the linear correlation between the temperature and EMR of long flame coal, gas fat coal and coking coal is linearly fitted. It is concluded that the EMR and temperature of coal with different metamorphic degrees are positively correlated when heated, and the EMR gradually increases with the increase of temperature. Based on this, the time sequence characteristics of EMR during the heating process of coal with different metamorphic degrees are further analyzed. During the heating process, the EMR signal has a significant long-range correlation, and it increases with the increase of time and temperature. (Kong *et al.* 2019b). Through the research, it is also concluded that the EMR signal generated by coal and rock under the load also has a corresponding relationship with the stress. With the continuous increase of stress, the degree of coal and rock deformation and fragmentation increases, and the EMR signal generated increases gradually (Ali *et al.* 2021, Gao *et al.* 2022). At present, the change rule of EMR signal of coal with different metamorphic degree and coal at different positions in the heating process is also the focus of the next research, which further provides support for the application of EMR technology to on-site monitoring.

6. Conclusions

- When coal is subjected to different temperature levels of treatments, the mechanical strength changes. Stress decreases with the increase of temperature, and the peak strain increases with the temperature rise. An increase in temperature enhances the continuity of the coal body and promotes the evolution of deformation and cracks of coal, therefore, mechanical strength of the coal is deteriorated. The relationship between the modulus of elasticity and temperature of coal is obtained by curve fitting, which indicates that the damage parameter of coal increases gradually with the increase of temperature.
- At different temperature stages, strength of EMR signals vary much. EMR signals generated by the coal under the temperature-pressure coupling condition is obviously higher than that of unconstrained heating condition. That is because the damage degree of coal under the condition of temperature-pressure coupling is obviously higher than unconstrained heating condition. Also, EMR signals under temperature-pressure coupling condition is more than the uniaxial condition. The EMR signal in the loading process increases gradually under the uniaxial condition, and there is a significant change when the coal body is unstable and destroyed. Under the condition of the temperature-pressure coupling, EMR signal can be noticed clearly during the whole loading process.
- Coal samples can generate two frequency bands when they are heated. The main frequency range of low frequency is 0-100 KHz, and the main frequency range of high frequency is 500~800 KHz. The main frequency of EMR under the condition of temperature-pressure coupling is high frequency, because complex damage to

coal causes migration of EMR main frequency signal from low frequency to high frequency. In the field test, the low-frequency and high-frequency antennas can be used simultaneously to collect all EMR signals generated in underground engineering.

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