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Numerical simulation of electromagnetic radiation caused by coal/rock deformation and failure

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A B S T R A C T

Based on the stress distribution characteristics and energy dissipation and release theories, a theoretical model of the electromagnetic radiation (EMR) in coal is established. The model is used in conjuction with rock failure process analysis software (RFPA) to numerically simulate the processes of coal/rock deformation and failure, the characteristics of the stress distribution and EMR in the processes, and the effects of the coal compressive strength and loading rate on the EMR. The results show that: (1) the EMR signals generated by coal samples under uniaxial compression increase with stress until the samples fail, and after that the EMR signals decrease rapidly. This is consistent with experimental results and belongs to group-shock type; (2) the EMR signals generated by rock samples under uniaxial compression reach their peaks at the time of main failure, and after that and in initial loading, the signals are weak. that is consistent with experimental results and belongs to main-shock type; (3) the greater the compressive strength of a coal sample is, more time delays its failure results in, and the higher the peak stress becomes; EMR signals generated in the breaking process of coal show an increasing trend. These results indicate that the theoretical model of EMR in coal can be used to study detailed EMR characteristics of coal in complex conditions.

1. Introduction

Coal/rock undergoing deformation and failure emits many forms of energy, among which is electromagnetic radiation (EMR). Cohen first proposed the term EMR in the 1920 [1]. Hulburt studied the emission effects of free electrons [2]. Between the 1960s and 1980s, Jordan studied nonlinear theoretical issues, such as effects of stress on the magnetic field, electric field, magnetic induction intensity and heat induction in elastic solids and unveiled a research direction on EMR emitted by elastic media under stress [3]. Hanson found EMR phenomenon during rock failure [4]. Thereafter, several researchers studied the characteristics of EMR emitted by marble, granite and other hard rocks, and applied the EMR in earthquake forecasting [5–8]. Studies on EMR produced by the deformation and failure of coal and other low strength rocks in coal-bearing strata started from 1990s. EMR from rocks and other brittle materials has been extensively investigated [9–15]. Chinese researchers studied EMR generation mechanism and emission characteristics during coal/rock failure [16–18]. By analyzing coal/rock EMR characteristics in the failure process, these researcher found that EMR could be used to determine the region of stress anomaly, and to monitor and forecast coal/rock dynamic disasters such as coal and gas outburst and rock burst. The main monitoring indicators of EMR include its intensity, pulse number and dynamic trends [19–24]. At present, although coal/rock EMR has been extensively studied both experimentally and theoretically, many issues remain unresolved, such as its characteristics, spatial distribution, affecting factors and characteristics under different sample scales, in particular if coal/rock are under complex loading conditions. Subject to laboratory testing conditions and coal sample preparation conditions (discrete samples), it is very difficult to conduct physical simulation. In addition, there are many interference factors, very poor repeatability and many uncontrollable influence factors to consider in the physical simulation tests. However, all of these could be simulated by numerical models.

The simulation of acoustic emission of coal/rock provides a reference for the emission of EMR. In recent years, numerical simulation technologies of coal have developed rapidly. In the late 20th century, researchers studied basic numerical simulation theories on brittle rocks during loading and failure, as well as release of acoustic energy in the failure process [25–26]. Then they put forth a new numerical simulation to solve problems related to rock mechanics [27], and developed a software RFPA for rock failure process analysis [28]. With this method, Chen, Tang,

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and others numerically simulated the rock failure process and acoustic emission characteristics in different loading conditions (uniaxial compression, shear, and triaxial) and achieved good results [29–32].

Based on damage mechanics, energy dissipation and equilibrium principle, we establish an electro-mechanical coupling model of coal/rock and its related EMR numerical simulation approach, described in this paper. Through the model and RFPA, we obtain the internal stress and strain distributions of loaded coal and rock. By means of the approach, we simulate the characteristics of coal EMR in deformation and failure and the effects of relevant mechanical parameters on EMR. The simulation approach not only provides a new experimental method for EMR study, but also reveals the generation mechanism, influential factors and applied technologies for EMR research.

2. Electro-mechanical coupling model (EMCM)

In essence, the deformation and failure of coal/rock mass are the results of the formation, development, combination, and integration of its internal micro-defects or micro-cracks under stress, that is, the consequence of internal damages in coal/rock. According to the mechanism of EMR by the charged electrons variable motion and the stress-induced polarization proposed by the author [17], coal/rock EMR is resulted from its internal inhomogeneity. The inhomogeneous deformation produced by coal/rock under stress, stimulates a lot of groups of vibrating dipoles, leading to occurrence of EMR; the variable motion done by the charged particles generated in the process of coal/rock failure can generate high-frequency electromagnetic radiation. It is obvious that EMR emitted by loaded coal/rock originates in their deformation and failure under stress, that is, the developed results of its internal micro-damages. Every unit (or volume element) in which deformation and failure occur has its contribution to EMR. In other words, EMR is positively proportional to the damage parameter of coal/rock materials.

According to the strain equivalent principle of damage mechanism (the statistical damage model proposed in [33]) and considering that material damage in the loading process is continuous, the followings are assumed: (1) the average elastic modulus of a coal/rock volume element without damage, E, obeys Hooke's Law before failure, i.e., the volume element is elastic; (2) the strength of every element obeys statistical law and Weibull distribution. So, EMCM of coal/rock EMR is put forth as follows:

$$\sigma = E\varepsilon\,(1-D), \tag{1}$$

$$D = \frac{1}{N_m}\sum N \tag{2}$$

$$\frac{\sum N}{N_m} = 1-\exp\left[-(\varepsilon/\varepsilon_0)^m\right], \tag{3}$$

where σ is the stress acted on the cross-section of sample [MPa], D is the dimensionless damage variable, and ΣN and N_m are the numbers of accumulative pulses at the time when the sample is subjected to the strain ε and to the strain ε_0 respectively. Eqs. (1)–(3) provide the basis for the numerical simulation of coal/rock EMR.

According to the principles of energy dissipation and release [34], and considering that one coal/rock element deforms under external stress, if this system is a closed one without heat exchange with its exterior in the process, the input energy applied by external work is U, then the energy of the coal/rock element in the state of complex stress satisfies the following relationships:

$$U = U_d + U_r \tag{4}$$

where U_d is the element dissipated energy, which is dissipated for its internal damage and plastic deformation; U_r is the element releasable energy.

In the principal stress space, various parts of energy in coal/rock unit can be expressed as [35]:

$$U = \int_0^{\varepsilon_1} \sigma_1 d\varepsilon_1 + \int_0^{\varepsilon_2} \sigma_2 d\varepsilon_2 + \int_0^{\varepsilon_3} \sigma_3 d\varepsilon_3, \tag{5}$$

$$U_r = \frac{1}{2}\sigma_1\varepsilon_{1,r} + \frac{1}{2}\sigma_2\varepsilon_{2,r} + \frac{1}{2}\sigma_3\varepsilon_{3,r}, \tag{6}$$

$$\varepsilon_{i,r} = \frac{1}{E_i}\left[\sigma_i - v_i(\sigma_j + \sigma_k)\right], \tag{7}$$

where $\varepsilon_{i,r}$ is the total elastic strain in the three principal stress directions, v_i is Poisson's ratio.

From Eqs. (6) and (7), the releasable energy stored in the volume element is related to elastic modulus and Poisson's ratio of the damaged volume element. For the convenience of engineering calculations, the primary elasticity E and Poisson's ratio v of the material are inserted into Eq. (6), the releasable energy of the volume element is then written as follows:

$$U_r = \frac{1}{2E}\left[\sigma_1^2 + \sigma_2^2 + \sigma_3^2 - 2v(\sigma_1\sigma_2 + \sigma_2\sigma_3 + \sigma_1\sigma_3)\right] \tag{8}$$

The releasable energy in the volume element would be released off as sound energy, EMR energy and other forms of energy.

Assuming that one volume element is damaged, it generates an EMR pulse. When the loaded element moves to the ith step, if the coal/rock is in the energy equilibrium, the energy released by all the elements in it at this time is:

$$E_i = \sum_{x=1}^{X} U_{x,r}, \tag{9}$$

where x is the number of the volume element in coal/rock sample, X is the total number. Thus, the EMR energy generated in the process of deformation and failure of the coal/rock sample, $E_{R,i}$ is:

$$E_{R,i} = \eta E_i, \tag{10}$$

where η is the ratio of the EMR energy $E_{R,i}$ to the total released energy from the coal/rock sample, its value range is between 0 and 1.

Assuming that the damage of the volume element fits the Mohr–Coulomb criterion, RFPA can be used to simulate the process of coal and rock deformation and failure, and to analyze the stress distribution and damage degree of each volume element in the loading process. Combined with EMCM, the macroscopic stress σ_i as the function of the corresponding macroscopic strain ε_i and the accumulative EMR pulses produced at the time of coal/rock failure $\Sigma N_i/N_m$ is calculated as follows:

$$\sigma_i = E\varepsilon_i\left(1 - \frac{1}{N_m}\sum N_i\right), \tag{11}$$

where E is the elastic modulus, i indicates the sample is loaded to the i-th step.

3. Numerical simulation method

The code RFPA is a convenient tool for EMR simulations. Based on the basic theory of finite element, it is the new numerical simulation software with considerations of characteristics of rock's nonlinearity, inhomogeneity and anisotropy. The system can be used: (1) to simulate the processes of the macroscopic