Study on Damage Mechanics Model of Mechanical and Electrical Couple of Three-dimensional Coal and Rock

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Abstract: Based on damage mechanics model of mechanical and electrical couple of one-dimensional coal and rock, damage mechanics model of mechanical and electrical couple of three-dimensional coal and rock is setup. Using the model, the relationship between electromagnetic radiation pulses, the amplitude and stress is analyzed. The effects of electromagnetic radiation and stress impacted by confining pressure conditions of the internal structure of coal and rock are simulated. Finally, electromagnetic radiation characteristics of sudden unloading uniaxial compression are analyzed. Application of research results show that: the model is reliable and advanced to analyze characteristics of damage mechanics of coal petrology.

Keywords: Damage mechanics; Coal petrology; Mechanical and electrical coupling

Whether in uniaxial compression, triaxial compression experiments, or in the mine underground mining process, due to the role of external forces, Coal and rock mass will engender deformation rupture, resulting in a series of phenomenon of electromagnetic radiation and acoustic emission. The change of electromagnetic radiation and acoustic emission signals can reflect the development of coal and rock deformation or micro-defects in the internal micro-cracks , while the deformation speed is determined by micro-element body and the size and rate of change of internal stress, and therefore the establishment of the damage mechanics model of three - dimensional force of coal and rock electro-mechanical coupling is very important for the effective prediction of dynamic disasters caused by the breakdown of coal and rock .

1 Damage Mechanics Model of Three Dimensional Mechanical and Electrical Couple of Coal and Rock

1.1 Damage Constitutive Relation of Three Dimensional Coal and Rock Mechanics

When coal and rock is pressed by the triaxial confining stress and the assumption $s_2 = s_3$, Function(1) can be available based on generalized Hooke's Law [1].

$$\begin{cases} s_1 = (l + 2G)e_1 + le_2 + le_3 \\ s_2 = (l + 2G)e_2 + le_1 + le_3 \\ s_3 = (l + 2G)e_3 + le_1 + le_2 \end{cases} \tag{1}$$

$s_1, s_2, s_3, e_1, e_2, e_3$ are respectively three principal stress and principal strain acted on infinitesimal body;
l, G —Lame constant。

1.2 the relationship between loading stress and electromagnetic radiation pulses

Adopt damage mechanics and statistical theory to put forward electrical coupling model in case of one-dimensional force, and then to get coal and rock material constitutive relation described by one-dimensional electromagnetic radiation pulses[2]:

$$s = Ee(1 - \frac{\sum N}{N_m}) \tag{2}$$

N_m— the total number of pulses of electromagnetic radiation generated by Coal and rockmass in case of a complete breakdown of coal and rock body.

$\sum N$—the cumulative number of pulses of electromagnetic radiation when the coal and rock strain is e, the strength of the infinitesimal body subject to statistical laws, here set to Weibull distribution:

$$f(e) = \frac{m}{e_0}\left(\frac{e}{e_0}\right)^{m-1} \exp\left[-\left(\frac{e}{e_0}\right)^m\right] \tag{3}$$

m, e_0 —distribution scale of Weibull distribution and shape parameters characterized by strain; e —Strain of coal and rock infinitesimal body;
Under the condition of $s_2 = s_3$, Function (4) can be get:

$$e_1 = s_c / E + s_3 /(2E) \tag{4}$$

This article assumes that once the rupture of micro coal and rock body will produce a significant number of electromagnetic radiation pulses, which makes a contribution for recording the total number of electromagnetic radiation pulses. Since the activities of the law of electromagnetic radiation is a statistical law, from equation (4), then coal or rock generated the probability of electromagnetic radiation pulses in the process of its deformation and damage [3]:

$$j(e) = \frac{m}{e_0}\left(\frac{e_1 - \frac{s_3}{2E}}{e_0}\right)^{m-1} \exp\left[-\left(\frac{e_1 - \frac{s_3}{2E}}{e_0}\right)^m\right] \quad (5)$$

Where $j(e)$ is the probability of the signal pulses of electromagnetic radiation when the confining pressure equals to s_3 and axial strain equals to e_1. If the randomness of intensity distribution of infinitesimal body is taken into account. The right-hand side of equation(5) can multipy with the the random number which can be assigned by the computer. Then equation (6) is available:

$$j(e) = RND(e_1)\frac{m}{e_0}\left(\frac{e_1 - \frac{s_3}{2E}}{e_0}\right)^{m-1} \exp\left[-\left(\frac{e_1 - \frac{s_3}{2E}}{e_0}\right)^m\right] \quad (6)$$

Random number $RND(e_1)$ changes along with the axial strain, the strain is greater so that its value is the greater , thus the greater the degree of infinitesimal body injury. So it produces the greater probability of the number of electromagnetic radiation pulses[4].

Assuming infinitesimal body will not be able to restore their strength when it is broken, that is to say the damage of coal and rock is irreversible in the process of its deformation. Along with the increase of deformation, the number of fracture infinitesimal body. Based coal and rock deformation arising from e to $e+de$,the increased number of electromagnetic radiation pulses is N, then N can be calculated by equation(7)[5]:

$$N = N_m \int_e^{e+de} j(x)dx \quad (7)$$

where $j(x)$ is the probability distribution function of coal and rock intensity, obtained by equation (5). So equation(8) is avaiable.

$$N = RND(e_1)\frac{m}{e_0}\left(\frac{e_1 - \frac{s_3}{2E}}{e_0}\right)^{m-1} \exp\left[-\left(\frac{e_1 - \frac{s_3}{2E}}{e_0}\right)^m\right] \cdot \Delta e \quad (8)$$

If s_3=0 we can get that

$$N = RND(e_1)\frac{m}{e_0}\left(\frac{e_1}{e_0}\right)^{m-1} \exp\left[-\left(\frac{e_1}{e_0}\right)^m\right] \cdot \Delta e \quad (9)$$

Namely, (9) is the relationship of the number of one-dimensional electromagnetic radiation pulses and strain .

When the coal and rock mass deformation reachs to e , the accumulated number of electromagnetic radiation pulses generated by coal and rock equals to $\sum N$, as follows:

$$\sum N = N_m \int_0^e j(x)dx \quad (10)$$

Assuming coal and rock deformation from e to $e+de$ corresponds to the maximum principal s_1 stress changes from s to $s+ds$, the equation (4) and equation (5) is substituted into by equation (7) to get the relationship between the principal stress and the number of electromagnetic radiation pulses[6].

$$N = N_m \int_e^{e+de} j(x)dx = N_m \int_s^{s+ds} \frac{m}{e_0}\left(\frac{s_1 - s_3}{Ee_0}\right)^{m-1} \exp\left[-\left(\frac{s_1 - s_3}{Ee_0}\right)^m\right] ds \quad (11)$$

Substituted into equation (10), you can get the relationship between the principal stress and the total number of electromagnetic radiation pulses as follows:

$$\sum N = N_m \int_0^e j(x)dx = N_m \int_0^s \frac{m}{e_0}\left(\frac{s_1 - s_3}{Ee_0}\right)^{m-1} \exp\left[-\left(\frac{s_1 - s_3}{Ee_0}\right)^m\right] ds \quad (12)$$

The above equations are the relationship between the principal stress and the total number of electromag netic radiation pulses. Simply if m=1 and $s_2 = s_3$ =const,then get:

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$$\sum N = N_m \int_0^e j(x)dx = C \cdot N_m \int_0^s \exp\left[-\left(\frac{s_1 - s_3}{Ee_0}\right)\right] d\left(-\frac{s_1 - s_3}{Ee_0}\right)$$
$$= C \cdot N_m \cdot \left(\exp\left[-\left(\frac{s_1 - s_3}{Ee_0}\right)\right] - 1\right) \quad (13)$$

And then to expand (13) with the Taylor series, you get the relationship between the accumulated number of pulses and the maximum principal stress, namely:

$$\sum N = C \cdot N_m \left[\frac{1}{2!} \cdot \frac{1}{(-Ee_0)^2} \cdot (s_1 - s_3) + \frac{1}{3\,!} \cdot \frac{1}{(-Ee_0)^4} \cdot (s_1 - s_3)^2 + \right.$$
$$\left. + \frac{1}{4!} \cdot \frac{1}{(-Ee_0)^6} \cdot (s_1 - s_3)^3 + \cdots \right] \quad (14)$$

(14) is expressed by n-polynomials, then get:

$$\sum N = a_n (s_1 - s_3)^n + a_{n-1} (s_1 - s_3)^{n-1} + \cdots + a_1 (s_1 - s_3) + a_0 \quad (15)$$

Thus, the relationship between the accumulated pulse number and process of coal and rock mass deformation and fracture of electromagnetic radiation generated by and difference of the maximum principal stress and the minimum principal stress difference $(s_1 - s_3)$ is nonlinear, can be seen as n-polynomial.For uniaxial compression, confining pressure $s_2 = s_3 = 0$, get:

$$\sum N = a_n s^n + a_{n-1} s_1^{n-1} + \cdots + a_1 s_1 + a_0 \quad (16)$$

If the confining pressure $s_2 = s_3 = 0$ under uniaxial compression, then when the maximum principal stress s_1 changes from $s_1(1)$ to $s_1(2)$, the number of pulses of electromagnetic radiation generated is represented as :

$$N = (a_n s_1(2)^n + a_{n-1} s_1(2)^{n-1} + \cdots + a_1 s_1(2) + a_0) - (a_n s_1(1)^n + a_{n-1} s_1(1)^{n-1} + \cdots + a_1 s_1(1) + a_0\ ) \quad (17)$$

When the stress change $\Delta s = s_1(2) - s_1(1)$ is very small, equation (14) can be approximated by using the following formula instead:

$$N = a_n \Delta s^n + a_{n-1} \Delta s^{n-1} + \cdots + a_1 \Delta s + a_0 \quad (18)$$

1.2 The Relationship Between Electromagnetic Radiation Intensity And Loading Stress

A electromagnetic radiation pulse sent by infinitesimal body of coal and rock in the process of its deformation and fracture under loading stress is equivalent to a field of energy radiated in unit time. The more pulses of electromagnetic radiation produced in unit time, the larger electromagnetic radiation energy sent to the outside. Suppose every pulse of electromagnetic radiation energy is the same, namelyW_0. According to the above theory and statistical theory analysis of coal and rock damage, the accumulated number of pulses of electromagnetic radiation generated under the maximum principal stress (axial stress) as s (or stress change Δs) can be obtained from (16) or (18). The total energy of the pulses of electromagnetic radiation the number under this condition is found as:

$$W = N \cdot W_0 \quad (19)$$

By electromagnetic theory, the relationship between instantaneous energyof electromagnetic radiation W_e and the intensity of electromagnetic radiation E_m can be got, the following function for the ralationship.

$$W_e = \int_V w_e dV = \int_V \frac{1}{2} E \cdot D dV = \frac{1}{2} e E_m^2 V \quad (20)$$

In function (20), E_m is the average electric field amplitude (intensity) of electromagnetic radiation field, D is electric displacement, V is the volume of coal and rock mass. If W=W_e, the relationship of the instantaneous intensity of electromagnetic radiation can be expressed by polynomial of loading stress from (16)~ (20):

$$E_m = f(s) = b_n \Delta s^n + b_{n-1} \Delta s^{n-1} + \cdots + b_1 \Delta s + b_0 \quad (21)$$

From the above theoretical analysis we can see that the relationship between the number of coal or rock deformation and fracture of electromagnetic radiation pulses and loading stress is non-linear. It can be expressed by polynomial.

2 Application of The Damage Mechanics Model of Mechanical and Electrical Coupling

From the coal and rock statistics and damage theory, the relationship between electromagnetic radiation pulses and intensity of coal and rock deformation and fracture and loading stress is studied to get a very strong coupling relationship between regularity for change of electromagnetic field of coal and rock deformation and fracture and regularity for change of stress field of infinitesimal body of coal and rock.The following will analyze the relationship between number and intensity of electromagnetic radiation pulses of coal or rock deformation and fracture and loading stress, then this paper will study characteristics of electromagnetic radiation under three-dimensional stress by the use of the mechanical and electrical coupling model.

2.1 The Relationship Between The Number of Pulses of Electromagnetic Radiation and Loading Stress

Figure1 is characteristic curves of the relationship between the accumulated number of electromagnetic radiation and acoustic emission pulses of uniaxial compression of coal sample K1. the corresponding regression equation as shown in Table 1. It is well known that the cubic polynomial can be fitted very well to show the relationship between the cumulative pulses number of electromagnetic radiation and the axial stress (MPa) from the diagrams and tables. the correlation coefficients is above 0.93.

2.2 Electromagnetic Radiation Characteristics Of Coal And Rock Samples Of Uniaxial Compression Under Sudden Unloading

The relationship between stress and electromagnetic radiation of uniaxial compression samples under sudden unloading is studied. the results are shown in Figure 2, then these can be seen that unloading characteristics of electromagnetic radiation in accord with coal and rock materials of uniaxial loading, while electromagnetic ra--diation gradually decreases with stress decreasing after unloading. The research results are consistent with the results of field experiment.

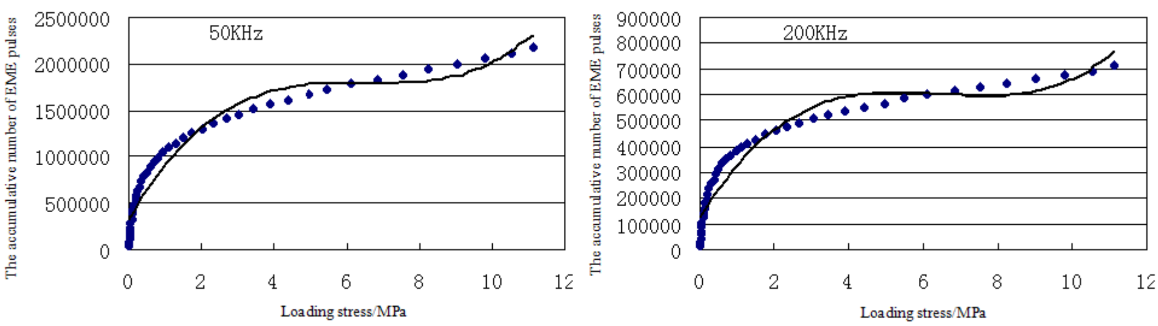
For the smaller heterogeneity of coal rocks, the number of electromagnetic radiation pulses after unloading is gradually decreased, while for the larger heterogeneity of coal rocks, the number of electromagnetic radiation pulses quickly reduces after unloading. This has a close connection with internal structure of coal and rock mass, so the smaller heterogeneity of coal and rock mass after unloading ,the greater damage and injuries will happen, in other words the larger homogeneous degree of coal and rock mass , the smaller damage and injuries will happen after unloading.

3 Conclusions

Based on the analysis of three-dimensional damage mechanics model of coal and rock materials, three dimensional coal and rock damage mechanics model of mechanical and electrical coupling is built. By analyzing the relationship between number of electromagnetic radiation pulses and loading stress and fitting experimental results, research results show that the relationship between accumulated number of pulses and stress is in line with polynomial relationship. By using the model to simulate the characteristics of electromagnetic radiation and stress - strain relations under conditions of the different confining pressures, research results show that the presence of confining pressure will increase the compressive capacity of coal and rock material, while the number of pulses of electromagnetic radiation and stress have a strong correlation, which can reflect the damage degree of coal and rock.

Table 1. Fitting results of cumulative number of pulses of electromagnetic radiation and acoustic emission and stress

Frequency	Fitting equation	Correlative coefficient R^2
50KHz	$y=5366.9x^3-104803x^2+679946x+325861$	0.9523
200KHz	$y=1993.9x^3-38560x^2+239912x+123144$	0.934
600KHz	$y=-81.47x^3-300.71x^2+915.45x-26.584$	0.9802
800KHz	$y=1923.5x^3-30567x^2+171516x+43009$	0.9543
1MHz	$y=22.479x^3-442.51x^2+2795.2x+904.63$	0.9619
50MHz	$y=1210.8x^3-21508x^2+170545x+14969$	0.9931



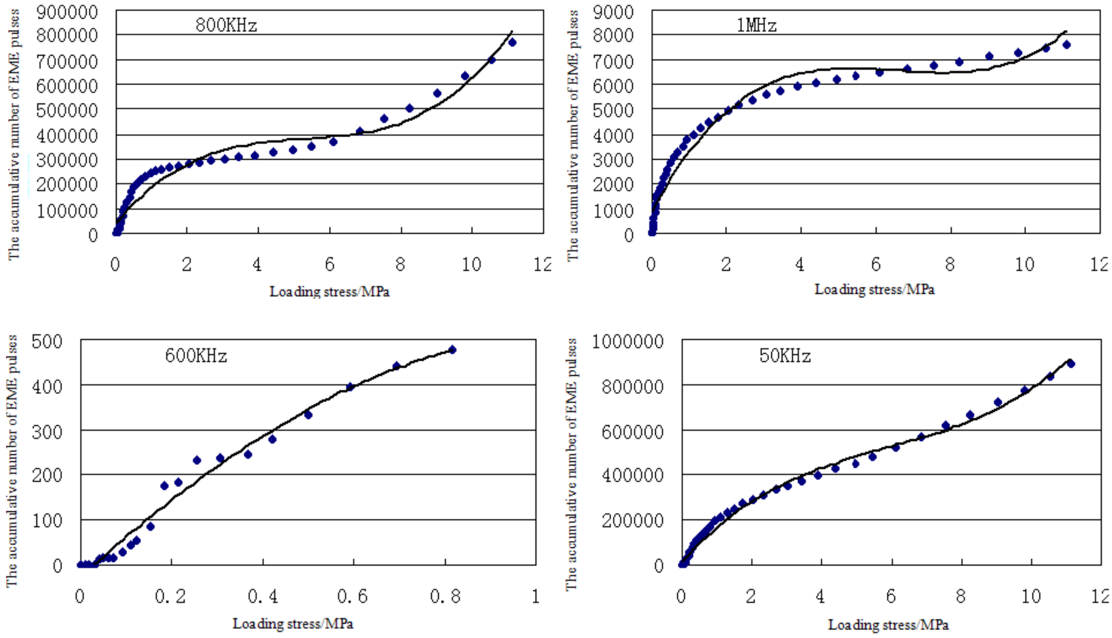


Figure 1. Fitting results of cumulative number of pulses of electromagnetic radiation and acoustic emission and stress

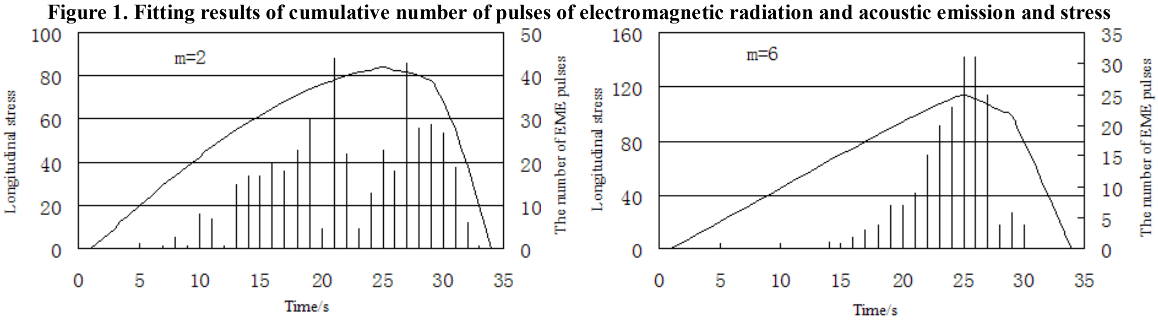


Figure 2. Time series of numberof electromagnetic radiation pulses under sudden unloading uniaxial compression（E=200,ε0=1）

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