AN EXPERIMENTAL STUDY ON THE DAMAGE AND ACOUSTIC EMISSION CHARACTER OF RAW COAL UNDER UNIAXIAL COMPRESSION CONDITION

by

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In the paper, the acoustic emission character is analyzed using a new damage variable which is defined based on ring-down count or energy count of acoustic emission and the damage model of raw coal under uniaxial compression is thus established. The results show that acoustic emission information can reflect internal damage of raw coal and is closely related with primary crack compression and evolutionary course of new crack generation, growth, and connectivity.

Key words: *rock mechanics, damage, compression tests*

Introduction

Coal is the most used energy in the world, coal resources account for 76% and 69% in China's primary energy production and consumption structure, respectively. It is predicted that in the next 50 years or even longer period of time, the growth rate of China's coal production and consumption will reach about 3.5%. Obviously, in the current and future for a long period of time, the strategic position of the coal industry in the economy of China is unshakable.

Up to date, people have never stopped the research of rock-damage. However, very few researches are conducted on the raw coal samples. Now, people have learned a little about the study of more than a century, people have got some knowledge on the problem of rock damage, achieved some initial results. In particularly, the application of hydraulic servo system and acoustic emission (AE) system deepened people's understanding of macro-mechanical characteristics and microscopic damage mechanism in the process of rock failure.

Assuming a rigid plastic body for matrix, Gurson [1] did a series of studies on the case of determining volume with holes using an analytical method. Horii *et al*. [2] and Nemat-Nasser *et al*. [3] assumed that the matrix is isotropic elastic body, he also modeled the case with cracks. In the field of statistical meso-damage mechanics, Xie *et al*. [4, 5] studied the issues related to rock damage and for the first time combined damage with rock creep deformation finite element analysis based on rock micro fracture mechanism.

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Many scholars have forced a lot of basic research in AE characteristics of the failure process of rock and coal, studies have shown that, we could infer the state change within a rock through the analysis and research of coal and rock AE signals, but most research are qualitative, therefore, how to contact AE parameters with rock (coal and rock) mechanical failure mechanism remains to be a further study. In this paper we proposed a conventional uniaxial compression test to better our understanding of the rock mass damage evolution loaded coal.

Uniaxial compression and acoustic emission test of coal

The experimental sample material is raw coal with a lower compressive strength, generally for 5 MPa. We processed several samples with the dimension of 50 mm × 100 mm from the same lump coal using crystal method partly.

The loading system adopts MTS815 hydraulic servo mechanical system, fig. 1, produced by MTS company of the USA. It is mainly used to test the mechanical properties and seepage characteristics of rock mass, concrete and coal under complex stress conditions. The test accuracy is high and the performance is stable. It can collect high and low speed data, and adopt control methods such as force, displacement, axial strain and transverse strain.

The AE monitoring system, PCI-2 rock-sound electrical data acquisition system in fig. 2, is produced by American Physical Acoustics, as an acoustic-electric data acquisition system, the equipment has five parts: pre-amplifier, filter circuit, A/D conversion module, waveform processing module, and computer.

Figure 1. The MTS 815 hydraulic servo mechanical system

Figure 2. The PCI-2 rock-sound electrical data acquisition system

During the uniaxial compression experiments, samples were first loaded to a maximum stress of 1000 N at a controlled loading rate of 50 N per second, and then unloaded at the same rate to zero. After that, we controlled displacement by the increment of 0.02 mm per minute to the failure of the samples. Same tests were repeated for three times.

Damage is meaning of mechanical properties decrease of materials produced by a large number of different shapes, defects for external force. Mechanical workers use an abstract *damage variable* to sum up the description of damage (the *damage variable* can be scalar, vector or tensor of rank two- order). Damage variable can be defined:

$$D = \frac{A_D}{A}, \ \Psi = \frac{A_{ef}}{A} \tag{1}$$

$$A = A_D + A_{ef} \tag{2}$$

$$D + \Psi = 1 \tag{3}$$

where D is the damage factor, Ψ – the continuity factor, A – the apparent cross-sectional area after damage of material, A_D – the appearing total area, and A_{ef} – the cross-sectional area of the actual bearing.

Then the initial condition of the damage evolution is $\Psi_0 = 1$, $D_0 = 0$. Internal damage of the samples has a constant development and expansion until the limited state (the broken or damaged destruction) due to external loads: $A_{ef} = 0$, $\Psi_f = 0$, $A = A_D$, $D_f = 1$. Due to the presence of initial defects, $D_0 > 0$. Samples cannot carry the loads before the effective area is reduced to a critical value, then $D_f < 1$.

External stress and deformation produces energy accumulation in rocks, this energy will release out in the form of elastic stress waves which is called AE phenomenon. Through the AE signal analysis and research of a rock, we can infer the evolution of the coal or rock in macroscopic aspects.

Essentially, the law of AE activity is a statistical regularity, therefore, it is bound to be consistent with the laws of the statistical distribution of the material internal defects. The total AE number $\Delta\Omega$ in a micro unit area ΔA can be written [6]:

$$\Delta\Omega = \frac{\Omega_m}{A_0}\Delta A \tag{4}$$

and the destructive area increment ΔA is given [6]:

$$\Delta A = A_0\phi(\varepsilon)\Delta\varepsilon \tag{5}$$

where A_0 is the area of the entire cross-section, Ω_m – the total AE number of the entire area, $\phi(\varepsilon)$ – the strain function, and $\Delta\varepsilon$ – the strain increment.

Therefore, the cumulated AE Ω is given as [6]:

$$\Omega = \Omega_m \int_0^{\varepsilon} \phi(x)\mathrm{d}x \tag{6}$$

where ε is a total strain.

If we adopt the Weibull model [7], we get:

$$\frac{\Omega}{\Omega_m} = \frac{m}{\varepsilon_0}\int_0^{\varepsilon}\left(\frac{x}{\varepsilon_0}\right)^{m-1}\exp\left[-1\left(\frac{x}{\varepsilon_0}\right)^{m}\right]\mathrm{d}x = 1-\exp\left[-1\left(\frac{\varepsilon}{\varepsilon_0}\right)^{m}\right] = D \tag{7}$$

where ε_0 is the initial strain, m – the power, and D – the damage variation.

As to the 1-D case, the constitutive relation of rock can be expressed:

$$\sigma = E\varepsilon\left(1-\frac{\Omega}{\Omega_m}\right) \tag{8}$$

where E is the modulus of elasticity.

Results analysis

Stress-strain curves of coal samples in uniaxial compression tests is an important means to describe the mechanical behavior of the coal materials, the curves show not only the compressive strength of the coal samples but also other parameters which are showing in tab. 1.

Table 1. Basic mechanical parameters of coal samples

Sample No.	E [GPa]	S_c [MPa]
I-1#	1.12	5.13
I-2#	1.05	4.62
I-3#	0.89	4.44

To conclude, the average compressive strength, S_c, is 4.73 MPa and 1.02 GPa for average Young's modulus, E. Raw coal is a kind of natural materials, and its unique internal structure determines a large difference from metals in discrete nature. Many factors account for the result, such as coal formation of the natural state, stress history and test conditions, even in the same acquisition and processing method, difference in the test results generated by the structure itself is very significant. Post collection and processing of samples can also cause difference in the results of the experiment, such as the parallel end portion control problems which often cause mechanical parameters of the experiment be in discrete nature. From tab. 1, we can already see that the coal samples are in different compressive strength and elastic modulus range, which increases the difficulty of test analysis.

Due to the stress-strain curves of the three coal samples have similar form of distribution, we now select one typical stress-strain curve showing in fig. 3.

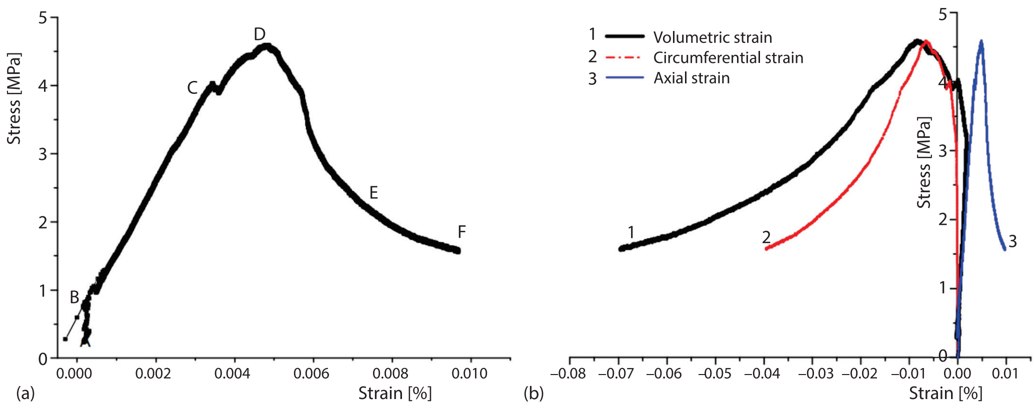

Figure 3. (a) Axial stress *vs.* strain curve and (b) volume strain *vs.* stress curve

Figure 3 reflects the trial coal samples with good ductility and the samples have a gentle process, differs from most brittle rocks' quick rupture, after peak stress. Figure 3(b) shows the relationship among different stress-strain development. It can be clearly seen from the diagram: the volume compaction point appears at a stress level of 3.25 MPa where the axial stress reaches 65% of the compressive strength. After then, the volume of sample increases rapidly along with the continuous destruction. Volumetric strain-stress curve reflects the general changes in the coal samples, when compressive stress reaches 75% (about 3.75 MPa) of the compressive strength, the volume strain is zero followed by volume expansion phenomenon.

In the test, AE signals recorded in the crash count and rise time, ring count, the energy count, amplitude, signal strength, and other relevant parameters, to thereby reflect the internal rupture of samples in the loading process. As the AE distribution curve in compressive strength test of each coal sample has a very similar form, this article lists only one representative of the AE curve in fig. 4.

We find the AE graphics in fig. 5 is similar to the three basic types of rock AE results observed by Mogi which means AE is well used in coal tests observation.

The curves of AE ringing count and AE energy count to time have very similar law. Contrast to the coal's stress-strain curve, it can be found that in the coal sample, AE law can be roughly divided into the following phases: initial closing segment, slow rising segment, the preceding paragraph before stress peak, the peak segment, and stable segment after stress peak.

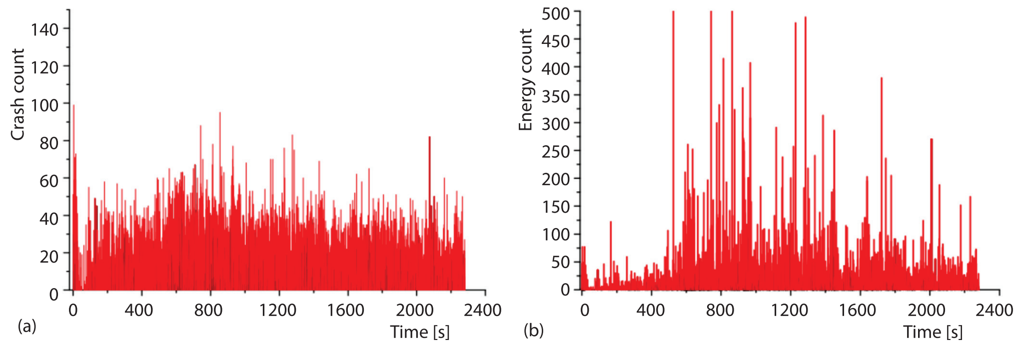

Figure 4. (a) Crash count *vs.* time and (b) energy count *vs.* time

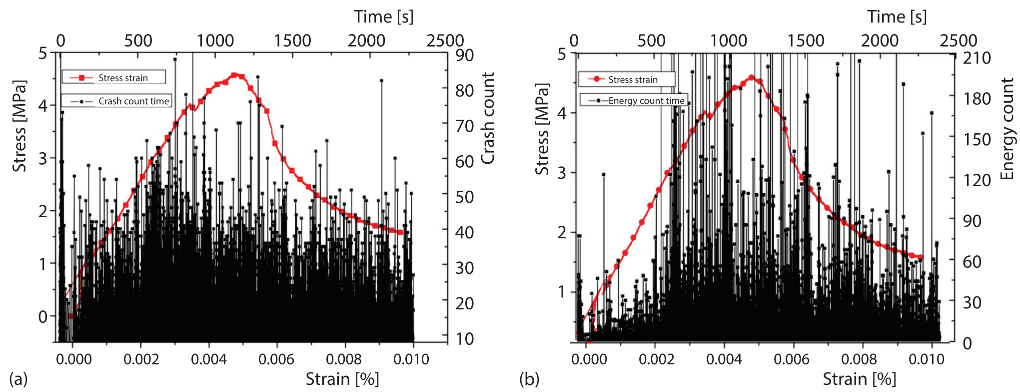

Figure 5. (a) Crash count-time *vs.* stress-strain and (b) energy count-time *vs.* stress-strain

Initial closing segment, corresponding to the stage of dense phase in the stress-strain curve, burst of AE signals generated by the micro-cracks in the coal samples and holes and weak joints surface due to compaction, the energy of this stage in the build-up state, the AE count cumulative curve will appear a first turning point.

Slow rising segment, the linear elastic stage in stress-strain theory, in this segment of the process, neither plastic deformation and crack propagation nor AE would exist. However, there are weak AE activities within the coal samples in this stage which represent weak damage. The ringing and energy count begin to rise steadily with the loading in the linear elastic stage, but they increase very slow and the elapsed time of this stage is relatively long.

The preceding paragraph before stress peak. When the loading is large enough to ensure the stress-strain curve gen into the weakening phase of transition from the linear elastic stage, which stress is about 65% of the peak stress, the AE ringing count shows a sharp increase. The factors is that there is much energy due to micro-cracks in the coal sample after compaction phase, linear elastic phase accumulation of energy, the evolution of minor injuries. When the energy meets a sudden release, the AE curve appears a rapid increment.

Peak segment. With the evolution of rock micro-cracks in sample, micro-cracks confluence to each other. Released energy continues to produce the elastic wave what has been in the high amplitude AE ringing (energy). The subsequent macroscopic cracks begin to form and throughout. The stress reaches the peak energy released in large quantities in the form of a stress wave, the maximum peak appears in the entire process of AE.

Stable segment. After the instability and failure stage, the stress of coal samples does not reduce to zero immediately a certain strength is maintained. We can also find the AE signal is quite clear that this is due to the cracking coal still in the event of breakage. When we load to an essentially unchanged stress, the AE decreased slightly, but there is still much signal, crack development does not stop.

By comparing the observations, fig. 6, we find the accumulated AE parameters increase linearly with time basically in coal's uniaxial compression test, there is just a slight change in the local (AE energy accumulated over time curve), and the coal samples under uniaxial compression are not obvious at all stages of the development of internal cracks. This is because the material used in the compression test is raw coal samples, they are loosely structured, timely developed with internal cracks and the dramatic release of a large amount of energy will not lead to the formation of large cracks.

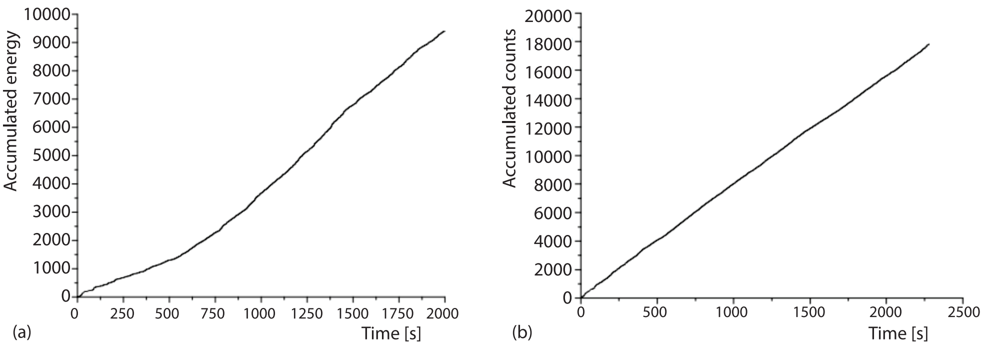

Figure 6. (a) Accumulated energy *vs.* time and (b) accumulated counts *vs.* time

In addition, we find that the AE curve of coal differs from high strength, brittle rock's AE curve. For common rocks, AE signal will soon enter the silence stage after the damage, and thereafter no longer produce the signal, while the coal AE test results indicate that even after sample's damage, loss of carrying capacity, the AE signals are still very large, this is because of the loose structure of coal.

Discussion

The progressive degradation of samples stiffness that results in the Young's modulus reduction and Poisson's ratio increase is primarily attributed to an increase in the level of crack damage within the samples. Either the extension of favorably-oriented, pre-existing cracks, the propagation of new cracks or some combinations of both. Each increased loads to the samples to a higher stress imparts an additional increment of crack damage to the sample, leading to increasing amounts of irrecoverable strain.

Previous AE studies of cracking in rocks or coals have demonstrated that, generally, new microcracks damage is generated only once of the previous maximum stress has been exceeded during loadings. This phenomenon was first reported in metals and is now known as the Kaiser *stress-memory* effect. However, the tests in this paper shows that, in our experiments, AE output re-commenced during any loading cycle at the same level of stress that it ceased during the unloading portion of the previous cycle. We do not therefore, see a classical manifestation of the Kaiser *stress-memory* effect. Before the samples were not held at the maximum stress for any extended period of time, crack damage did not have time to equilibrate to the level of applied stress. Consequently, time-dependent subcritical cracking continues during a small portion of the unloading part if there is.

Conclusion

The AE activity of coal has a corresponding trend with the stress-strain curve. Overall, coal AE laws can be broadly divided into the following phases: initial closing segment, slow rising segment, the preceding paragraph before stress peak, the peak segment, and stable segment after stress peak, but the various stages of the distinction is not obvious. When the stress reaches about 65% of the coal peak stress, AE activity begins to intensify, the number AE activities reach the peak to the peak stress and remains stable after then. The curves of accumulated energy and count over time show two approximate linear because of the soft coal, more internal cracks, the discrete strong, no obvious damage stage. The development of coal-rock deformation and damage can be regarded to be gradual, which is the whole process from deformation and damage initiation and evolution the appearance of macroscopic cracks, from macroscopic propagation damage.

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Nomenclature

A_D – appearing total area, [m^2]
A_{ef} – cross-sectional area of the actual bearing, [m2]
D – damage factor, [–]
E – modulus of elasticity, [Pa]

Greek letters

ε – strain, [–]
σ – stress, [Pa]

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