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ACOUSTIC EMISSION AND DAMAGE CHARACTERISTICS OF ANTHRACITE UNDER DIFFERENT CONDITIONS

AKUSTIČNA EMISIJA IN ZNAČILNOSTI POŠKODB ANTRACITA PRI RAZLIČNIH POGOJIH

Jiyu Zheng[1,2], Xiaohua Jin[3*], Kunyun Tian[2], Yinbo Zhou[2]

[1]School of Energy Science and Engineering, Henan Polytechnic University, Jiaozuo, Henan 454000, China
[2]School of Resources and Safety Engineering, Henan University of Engineering, Zhengzhou, Henan 451191, China
[3]School of Energy and Environment Engineering, Zhongyuan University of Technology, Zhengzhou, Henan 450007, China

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Acoustic emission (AE) can be used to observe the process of coal fracture propagation. Based on a press and acoustic-emission platform, the damage and acoustic-emission characteristics of anthracite with different loading rates, water amounts and sizes were studied. The results show that there is less acoustic emission in the initial compression stage of coal; acoustic emission is more active in the transition from elastic deformation to plastic deformation, which is manifested in the following aspects: the faster the loading rate, the higher is the number of acoustic-emission events; the peak count of acoustic emissions of a saturated-coal sample is significantly lower than that of a natural-coal sample. Coal samples and large coal samples emit even more sounds. Based on the normalization of acoustic-emission counts, the relationship between damage variables and stress-strain is studied, and it is characterized by an initial slow increase, followed by a rapid increase; however, different factors have a great influence on the damage-characteristic curve. The research results have a certain guiding significance for the coal and rock disaster prediction.

Keywords: anthracite, influencing factors, acoustic emission, damage characteristics

Akustično emisijo (AE) lahko uporabimo za opazovanje procesa napredovanja preloma plasti premoga. Avtorji, so na osnovi obremenitev pod tlakom in akustične platforme, študirali poškodbe in značilnosti akustične emisije antracita pri različnih hitrostih obremenjevanja, vsebnosti vode in velikosti. Rezultati preiskav so pokazali, da je manj akustične emisije v začetnih stadijih obremenjevanja premoga. Akustična emisija je bolj aktivna pri prehodu iz elastične v plastično deformacijo, ki se izraža na naslednje načine: a) višja, kot je hitrost obremenjevanja, višje je število akustičnih dogodkov in b) maksimum akustične emisije z vodo nasičenega vzorca premoga je pomembno manjša, kot akustična emisija vzorca iz naravnega premoga. Vzorci premoga večje velikosti celo bolj akustično zvenijo. Avtorji so na osnovi normalizacije števila zvenov akustične emisije, študirali zvezo med spremenljivkami odgovornimi za poškodbe in krivuljami napetost-deformacija, za katere je značilen najprej počasen in nato hiter razvoj poškodb. Avtorji ugotavljajo, da imajo različni faktorji velik vpliv na obliko krivulje poškodb in da podani rezultati raziskave predstavljajo dobro vodilo za napoved nesreč zaradi preloma plasti premoga ali skalovja.

Ključne besede: antracit, vplivni faktorji, akustična emisija, karakteristike poškodb

1 INTRODUCTION

The internal structures of materials change under the action of force, and elastic waves are produced in the process of structural changes. Therefore, acoustic emission is a phenomenon of transient elastic waves generated by a local rapid release of energy in materials. A coal body is a heterogeneous porous medium and there are two systems of pores and fractures. Acoustic emission (AE) is produced in the process of stress. Therefore, there is a significant correlation between a coal-deformation process and acoustic emission. Acoustic emission (AE) has become an important non-destructive monitoring method in the prevention and control of coal-rock burst disasters and is widely used in underground space engineering.

With the increasing difficulty of building deep mines and super long tunnels, higher requirements for monitoring the stability and damage degree of coal and rock during constructions are put forward. Acoustic emission is a more stable and reliable monitoring method. Acoustic emission is used in underground engineering, mainly for monitoring the stability of surrounding rocks (stress and strain observation), coal and rock mass damage (fracture observation) and rock burst monitoring.[1,2] T. Shiotani[3] determined the mechanism of an acoustic-emission source based on the characteristics of the acoustic emission. X. G. Yin[4] studied the quiescence and fractal characteristics of acoustic emission during rock failure. K. Kusunose's[5] triaxial compression tests were carried out on granites with different texture distributions, and the fractal dimension of the spatial distribution of AE events was analyzed. L. Zhucai[6] carried out an experimental study on the resistivity and acoustic-emission response characteristics of sandstone samples during the whole process of uniaxial compression. The analytical expression of damage variables of rock samples based on a resistivity characterization was derived. G. Kwiatek[7] ob-

*Corresponding author's e-mail:
xiaohjin@yeah.net (Xiaohua Jin)

tained a new understanding of the fracture process of hard rock by monitoring the acoustic emission (AE) in the process of a fatigue hydraulic fracture test of a hard rock. T. Ishida[8] used AE monitoring equipment to study the distribution characteristics of an AE source in the process of a dislocation test. G. Manthei[9] studied the acoustic-emission characteristics of rock samples under triaxial compression using acoustic-emission probes and concluded that most of the acoustic-emission events occurred due to tensile cracks caused by rock dilatation. A. Chmel and I. Schherbakov[10] studied the acoustic-emission characteristics and energy release of granite under impact loading. Alkan[11] determined the dilatancy boundary of a salt rock by studying the acoustic-emission characteristics at different strain stages in a triaxial compression test. L. G. Tham[12] used a multi-channel acoustic-emission monitoring system and finite-element software to study slate under a tensile stress state; P. Ganne[13] studied brittle failure of a rock just before its peak, and summarized four stages of the rock acoustic-emission energy accumulation. S. Q. Yang and H. W. Jing[14] comparatively analyzed the AE characteristics of intact sandstone and sandstone with a single fracture in different failure stages, indicating that the AE information can better reflect the variation of internal cracks in a rock. Y. Filimonov[15] found that the higher the loading rate, the more obvious is the acoustic emission of rock salt. L. Baoxian[16] proposed a damage variable based on the normalized cumulative acoustic-emission count and established a uniaxial-compression damage model of coal and rock, which better reveals the damage-evolution law of loaded coal and rock. The acoustic-emission characteristics of fiber-reinforced concrete under the conditions of a fracture process, layered cyclic unloading and irregular complex structures are studied in the literature.[17–19] F. Ren[20] studied the spatiotemporal evolution and damage of microcracks in schist under true triaxial compression and strain-fracture tests using the acoustic emission (AE) localization technique and moment tensor analysis method. Compared with the published literature, this study has its own characteristics. Based on anthracite materials, this study considers the influencing factors of acoustic emission of anthracite, characterizes the damage

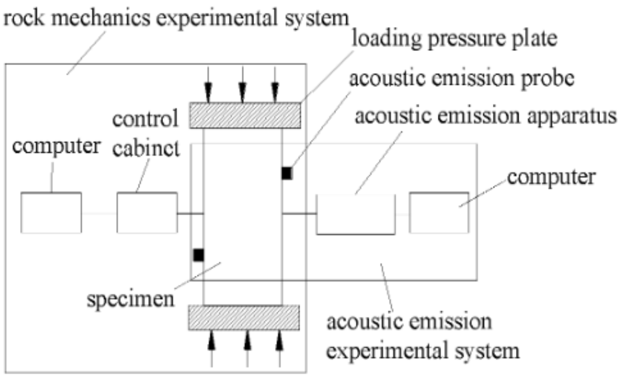

Figure 1: Acoustic emission experimental device

of coal by acoustic-emission counting and introduces the concept of a damage variable. These research topics are integrated and rarely studied in the published literature.

Uniaxial compression is a common stress state of underground coal. The coal seam and the wall of the working face are under uniaxial stress. Especially in the coal face, there are crack expansion and gas emission due to uniaxial compression so the study of uniaxial-compression-coal acoustic-emission characteristics is carried out to understand the state of the coal face before a crack-propagation process; rock-burst and gas control has a significant role.

2 EXPERIMENTAL DEVICE

The RMT-301 rock-mechanics experiment system and Soft Island acoustic-emission system were used. The rock-mechanics experiment system issues instructions from the computer to the control cabinet, which controls the press for mechanical loading. The acoustic emission (AE) system connects the AE probe to the AE instrument by pasting the AE probe onto the surface of a specimen. The collected AE signals are transmitted to the computer through the AE instrument.

3 STRESS-STRAIN AND ACOUSTIC-EMISSION CHARACTERISTICS OF ANTHRACITE

The stress-strain curve of the coal and rock under uniaxial compression can be divided into four stages: compaction stage, elastic-deformation stage, plastic-deformation stage and failure stage. From **Figures 2** to **6**, it can be seen that in the initial loading stage, there is low, or even zero, acoustic-emission activity; the initial crack in the coal and rock begins to close and a small amount of acoustic emission is produced during the closing process; a failure of part of the rough surface occurs after closing and there is a slip between the closed crack and the surface, while the energy is low. With a slow increase in the load, the crack begins to propagate. New cracks begin to appear; acoustic-emission count, cumulative-sounding count and energy rate gradually increase. As the loading continues, the interaction between the cracks begins to intensify; microcracks coalesce, penetrate and gradually form macro-cracks. Near the peak value of the stress, AE activity is very intense and AE count reaches the maximum value at the peak value of the stress.

In reality, the geological environment of a coal body is very different and the movement speed of coal face, coal-water content and coal-seam thickness all have an impact on acoustic emission. As can be seen from the acoustic-emission count, during the loading process, acoustic emission is more active when the elastic deformation transforms into plastic deformation, and the acoustic-emission count reaches its maximum when the coal is damaged.

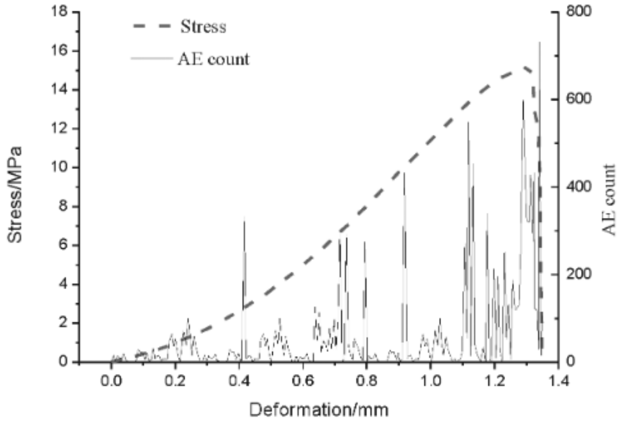

Figure 2: Characteristics of acoustic emission (loading rate of 0.01 mm/s)

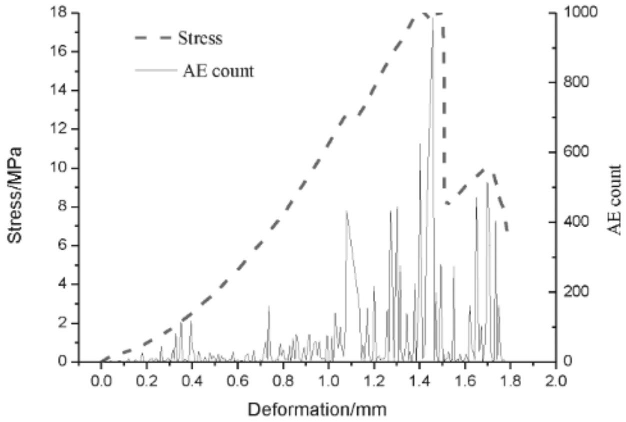

Figure 4: Characteristics of acoustic emission (the natural state)

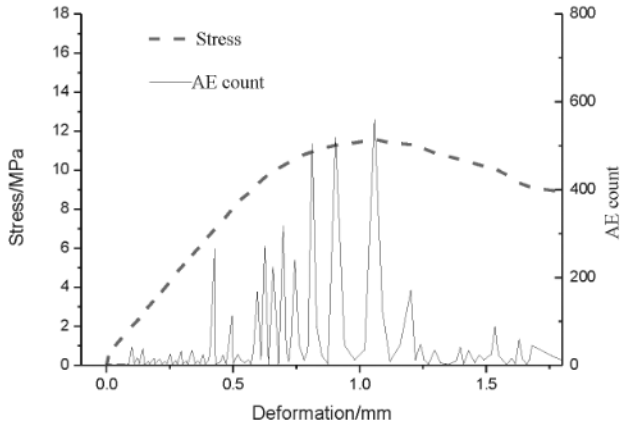

Figure 5: Characteristics of acoustic emission (the saturation state)

When the coal face is not moving at the same speed, the overburdened layer exhibits a different loading rate. Therefore, we can observe the acoustic-emission characteristics of coal under different loading rates through experiments. The mechanical characteristics and acoustic-emission characteristics of coal vary greatly with the loading rate. Specifically, the faster the loading rate, the more obvious are the brittle-failure characteristics of anthracite; the faster the loading rate, the higher is the number of acoustic-emission events and the higher is the frequency. When the loading rate is 0.01 mm/s, the maximum AE count is 732; when the loading rate is 0.02 mm/s, the maximum AE count is 1142 (as shown in **Figures 3** and **4**).

The strength and acoustic-emission characteristics of the saturated coal samples are obviously different with different water amounts. The uniaxial compressive strength of the saturated coal samples is smaller, the peak deformation is smaller, but the post-peak deformation is larger. The strength of the coal samples in the natural state is higher, the deformation in the whole failure process is larger and the duration of the elastic-deformation stage is longer (as shown in **Figure 3**). The smaller the moisture amount, the more brittle are the natural coal samples. Compared with the natural coal samples, the peak number of acoustic emission of the saturated coal samples decreases significantly (as shown in **Figure 4**).

The peak strength of a coal sample is negatively correlated with its size: the smaller the size, the lower is the compressive strength (**Figure 5**); when the size of a coal sample is small, the acoustic emission occurs earlier and the sounding count first shows a gradual increase and then a decrease. When a rock sample is large, the AE number is small before the peak stress and significant

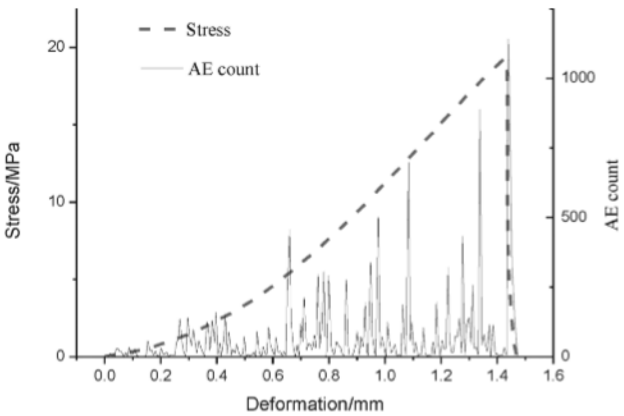

Figure 3: Characteristics of acoustic emission (loading rate of 0.02 mm/s)

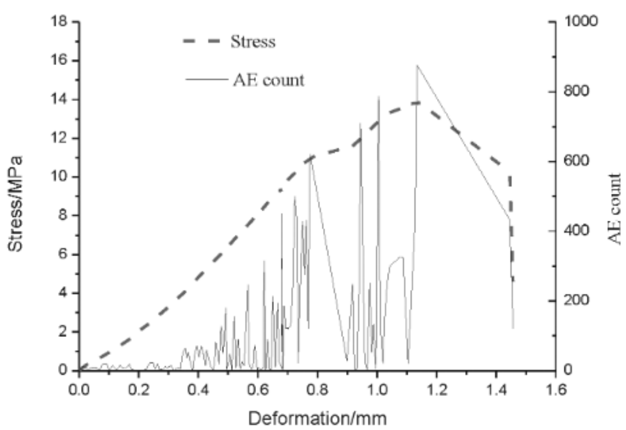

Figure 6: Characteristics of acoustic emission (size of 50×50 mm)

AE events suddenly erupt at the peak stress. The AE model belongs to the sudden-emission type. Compared to a small coal sample, the large-coal-sample sounding count is larger.

3 DAMAGE VARIABLE AND ACOUSTIC EMISSION

Sounding count is one of the characteristic parameters, which can better reflect the change of material properties when describing the characteristics of acoustic-emission signals because it is proportional to the motion of dislocations, exfoliation and fracture of inclusions and second-phase particles and the strain energy released due to crack propagation.

L. M. Kachanov[21] defines the damage variable as:

$$D = \frac{A_q}{A} \tag{1}$$

where A_q is the area where all the micro-defects on the cross-section are loaded, and A is the area of the initial losslessness.

If the cumulative acoustic-emission count for a complete failure of the whole cross-section A of a nondestructive material is C_0, the acoustic-emission count C_w for the unit-area element failure is C_w:

$$C_w = \frac{C_0}{A} \tag{2}$$

When the section damage area reaches A_d, the cumulative acoustic-emission count C_d is:

$$C_q = C_w A_q = \frac{C_0}{A} A_q \tag{3}$$

So there is:

$$D = \frac{C_q}{C_0} \tag{4}$$

According to the stress-strain and damage variable curves, the damage evolution of uniaxially compressed coal and rock can be divided into three stages: the initial damage stage, the damage stability evolution and development stage, and damage-acceleration development stage.

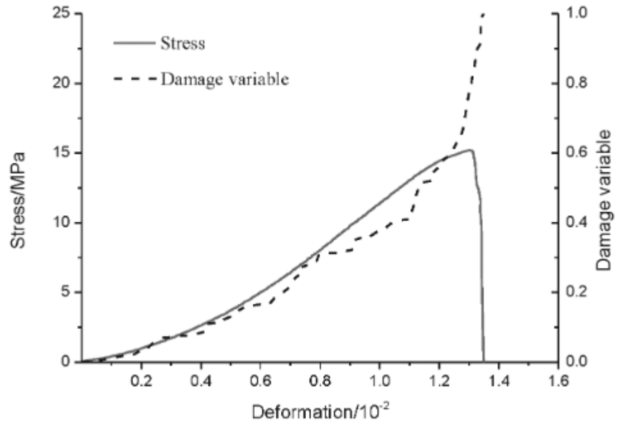

Figure 7: Damage characteristics (loading rate of 0.01 mm/s)

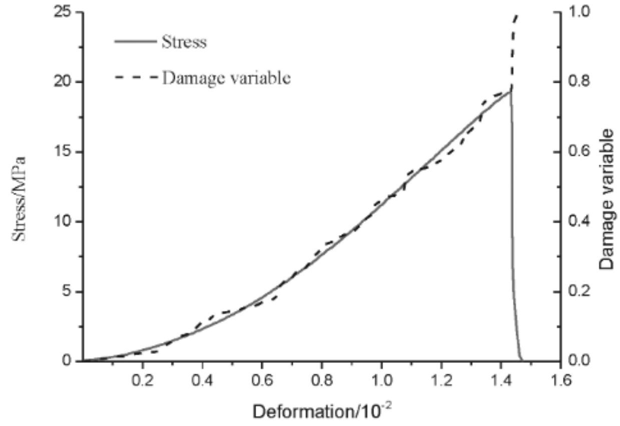

Figure 8: Damage characteristics (loading rate of 0.02 mm/s)

In the natural state, the loading rate is different (**Figures 6** and **7**), but the damage variable shows a slow increase at first and then a rapid increase. However, at the peak stress, the faster the loading rate, the greater is the damage variable, indicating that the faster the loading rate, the more accumulative is acoustic emission.

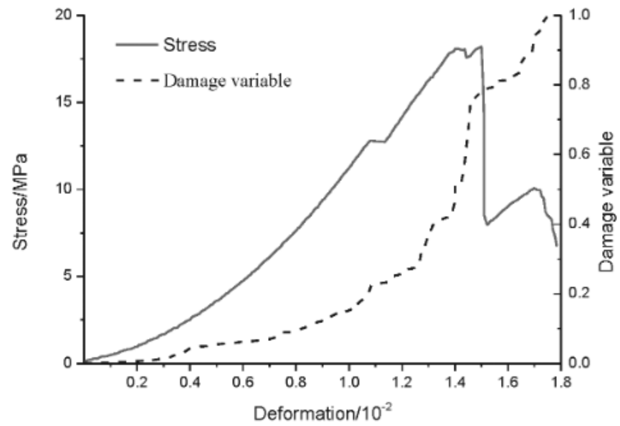

Figure 9: Damage characteristics (the natural state)

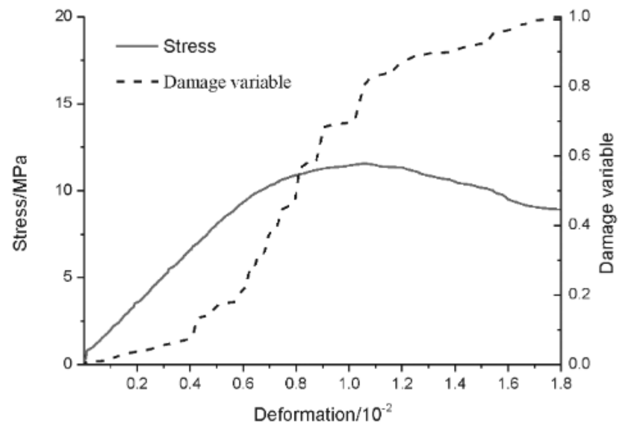

Figure 10: Damage characteristics (the saturation state)

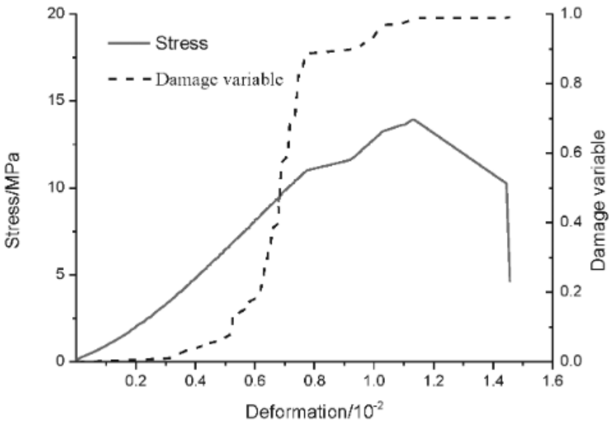

Figure 11: Damage characteristics (size of 50×50 mm)

The damage characteristic curve of saturated coal is quite different from that of natural coal (as shown in **Figures 8** and **9**). Compared with natural coal, saturated coal shows better plasticity. Therefore, coal samples are not completely destroyed after reaching the peak stress and there is still a slowly increasing damage curve after destroying.

In order to investigate the effect of size on damage variables, cylindrical specimens with a diameter of 50 mm and a height of 50 mm were selected. Compared with the standard specimen (50 mm in diameter, 100 mm in height), the damage characteristic curve for the smaller coal sample increases slowly at first and then rapidly (**Figure 10**). At the plastic stage, the curve increases slowly, indicating that the acoustic emission of the smaller coal sample mainly concentrates before the plastic stage. After loading to peak stress, the curve is approximately horizontal.

4 CONCLUSIONS

The factors considered in the uniaxial compression tests are closely related to the mining process. The loading rate corresponds to the mining speed, the moisture content corresponds to the coal moisture content and the size effect corresponds to the mining thickness. The following conclusions are obtained through experiments and analyses:

1) In uniaxial compression tests, anthracite is brittle and its peak strain is small. The loading rate, moisture content and size effect have a certain influence on the stress curve of anthracite. The faster the loading rate, the greater is the peak stress; the higher the moisture content, the smaller is the peak stress and the stronger is plasticity. The smaller the size, the smaller is the peak stress.

2) The characteristics of acoustic emission of coal are closely related to the compression failure of coal. In the initial compression stage, acoustic emission is low; during the transition from elastic deformation to plastic deformation, acoustic emission is more active; with the failure of coal, acoustic emission reaches the maximum value.

3) Based on the normalization of acoustic-emission counts, the relationship between damage variables and stress-strain is studied, showing that the curve initially slowly increases, and during the elastic and plastic stages it rapidly increases. Specifically, at the peak stress, the faster the loading rate, the greater is the damage variable. Saturated coal shows better plasticity and the damage curve is still slowly increasing after the failure. The damage characteristic curve for the small coal sample increases slowly at first, then it increases rapidly, and again increases slowly at the plastic stage. The research results have a certain guiding significance for coal and rock disaster prediction.

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