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Study on correlation of acoustic emission and plastic strain based on coal-rock damage theory

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Abstract. The high positive correlation between plastic strain of loaded coal-rock and AE (acoustic emission) characteristic parameter was studied and proved through AE experiment during coal-rock uniaxial compression process. The results show that plastic strain in the whole process of uniaxial compression can be gained through the experiment. Moreover, coal-rock loaded process can be divided into four phases through analyzing the change of the plastic strain curve : pressure consolidation phase, apparent linear elastic phase, accelerated deformation phase, rupture and development phase, which corresponds to conventional elastic-plastic change law of loaded coal-rock. The theoretical curve of damage constitutive model is in high agreement with the experimental curve. So the damage evolution law of coal rock damage can be indicated by both acoustic emission and plastic strain. The results have great academic and realistic significance for further study of both AE signal characteristics during loaded coal-rock damaged process and the forecasting of coal-rock dynamic disasters.

Keywords: loaded coal-rock; plastic strain; acoustic emission; unloading modulus; damage

1. Introduction

With the increasing of mining depth, the frequency of coal-rock dynamic disasters is getting higher and higher. It is still a major problem to predict the dynamic disasters in both mining safety and rock mechanic fields. Acoustic emission (AE) technique is a new method for dynamic disaster prediction applied to disaster prediction of coal and gas outburst (Nie *et al*. 2003, Gao *et al*. 2014, Shi and Li 1998), rock burst (Liu *et al*. 2015, Tan *et al*. 2007), surrounding rock deformation (Cai and Xiao 2006, Xiao and Zhu 2013), landslide, earthquake (Zhou *et al*. 2005) and rock or concrete construction instability (Lai *et al*. 2015). Internal state change of loaded rock can be inferred by AE signal feature, and then the rock failure mechanism can be got by inversion. Researches on AE features of coal-rock have been carried out through positioning study on coal samples under uniaxial compression, Masahiro *et al*. (1988) found that the AE source distributes in stripe type along with fractures. Satoshi and Watanabe (1988) made a quantitative research on the relationship between drilling diameter and AE parameters which measured the coal seam stress distribution by AE technology. Shkuratnik *et al*. (2004) studied the AE features of compressed and fractured coal and rock under different loading modes. Aggelis *et al*. (2016) applied AE during four-point

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bending tests of large beams to follow the damage accumulation to determine the onset of fracture as well as the different damage mechanisms through the registered shifts in AE rate. In China, Cao *et al*. (2007) made comprehensive analysis on outburst coal deformation which shows that AE feature of coal deformation and fracture can be better reflected by ringing count ratio. Liu *et al*. (2007) divided the AE feature into 4 phases after researches on the deformation and AE features of uniaxial compression remodeling coal samples. Wang *et al*. (2004) studied the AE spectrum features during the deformation and fracture process of uniaxial compression coal samples, and found that the AE spectrum feature has close relationship with coal deformation and fracture process. Fan *et al*. (2016) introduced acoustic emission nondestructive detecting technology into a series of fracture tests to observe the internal damage of concrete in real time.

For rock material of engineering specifications, plastic strain is the macro performance of crack initiation, development and accumulation inside the rock (Yin 1995), and acoustic emission is defined as a kind of elastic wave which generated by sudden energy release caused by micro fracture in the process of material deformation (Zhao *et al*. 2007). It is clear that both plastic strain and acoustic emission generate from the micro fracture inside the coal and rock mass. So in this paper, we take a try to reveal the internal mechanism of coal-rock deformation through experimental on the correlation between the AE features and elastic strain of coal samples during the compression and deformation process. The result will be a new evidence for coal-rock dynamic disaster valid prediction by AE technology.

2. Acoustic emission mechanism of coal and rock

With the action of outside compression, the stress concentration will appear due to the uneven internal structure and the existence of various defects, which leads to instability of stress distribution. When strain energy accumulated by the stress distribution instability reaches to a certain degree, the stress will get redistribution and reach a new stable state. Things like plastic flow, micro fracturing, dislocation occurrence and accumulation and fracture development always happen in these processes, which is actually the releasing process of strain energy. The part of the energy will be transmitted in stress wave, which is named ‘acoustic emission’ (Yuan *et al*. 1984) From above, there are two necessaries for the AE phenomenon: one is the outside compression action on material, another one is structural non-uniform or defect inside material. Dynamic information of micro deformation and cracking and crack development inside material can be obtained through the AE mechanism and technology. The AE source is the head stream of material devastation. Because of the AE activity happening earlier during the deformation process, we can not only infer the current state of AE resource but also figure out the formation history and the development tendency prediction through the AE feature and emission intensity, which can go ahead the state of monitoring and fault diagnosis.

3. Plastic strain analysis of loaded coal-rock

According to previous experiments, both elastic and plastic deformations of coal and rock mass will be happened in the loading process. The unrecoverable deformation after complete discharge is named plastic deformation and the recoverable deformation is named elastic deformation. E_U is defined as unloading modulus under uniaxial compression condition (see Fig. 1).

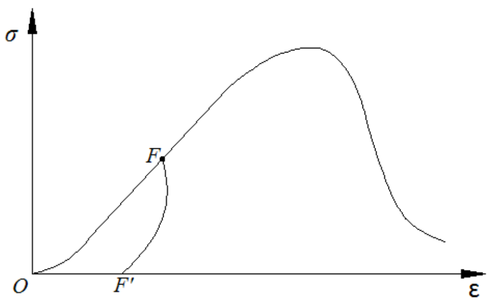


Fig. 1 Stress-strain curve of coal and rock

$$E_U = \sigma_F / (\varepsilon_F - \varepsilon_{F'}) \tag{1}$$

Where σ_F is stress at point F; ε_F is strain at point F; $\varepsilon_{F'}$ is strain at point F'.
Thus, plastic strain at point F is

$$\varepsilon_{PF} = \varepsilon_F - \varepsilon_{eF} = \varepsilon_F - \sigma_F / E_U \tag{2}$$

Where ε_{PF} is plastic strain at point F; ε_{eF} is elastic strain at point F. Thus, plastic strain at any point on the stress-strain curve can be obtained.

4. Experiments

One group of uniaxial cyclic loading experiment and one group of uniaxial compression experiment for coal-rock samples are respectively carried out, and the unloading modulus E_U, plastic strain ε_P and AE feature parameters are obtained. The experimental process and results are as follows:

4.1 Experimental facilities and project

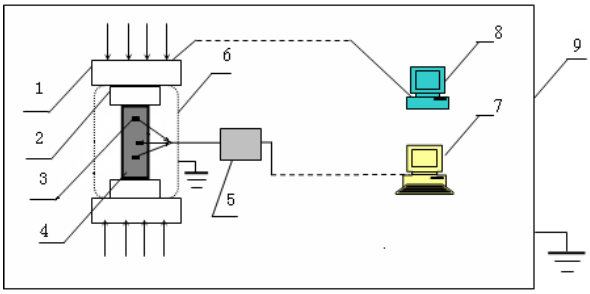
4.1.1 Experimental facilities

The coal-rock uniaxial compression and damage acoustic-electric testing system is consisted of YAW series microprocessor control electricity-liquid servo pressure testing machine and CTA-1 acoustic-electric data acquisition and processing system. The whole experiment system is located in GP6 efficient electromagnetic shielding system as Fig. 2 shows.

Cal-rock damage and the AE features test is carried out based on the experimental system. AE signal pulse value and energy value are recorded through CTA-1 acoustic-electric data acquisition and processing system. Parameters such as loading value, displacement and time are automatic recorded by YAW series microprocessor control electricity-liquid servo pressure testing machine.

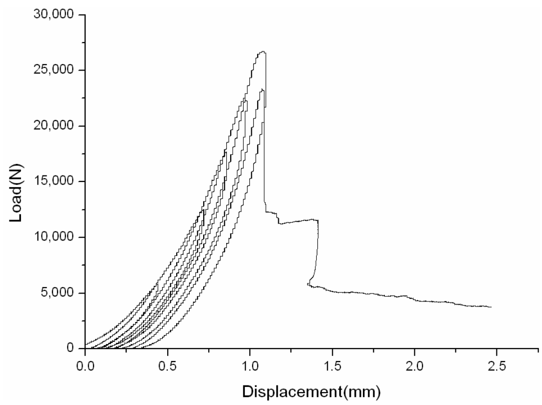
4.1.2 Sample preparation

Experimental samples are taken from 18th coal bed in Nanshan coal mine. Coal samples are made into standard samples of Φ50 mm × 100 mm. Flatness error of two end faces for the standard sample is less than 0.02 mm. All processed samples need strict filtrating: (1) get rid of samples with obvious fracture and visible cracks on surface; (2) get rid of samples of dissatisfactory size

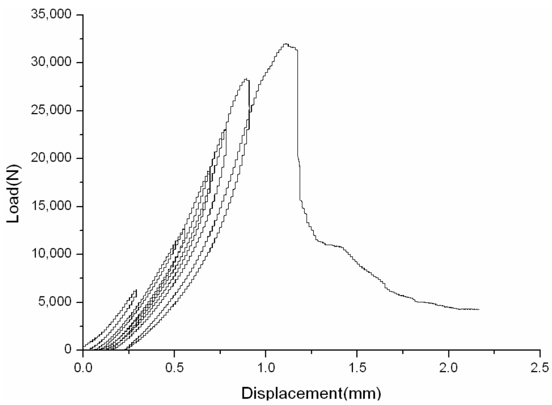


1 – pressure testing machine; 2 – insulated shim; 3 – acoustic-electric sensor;
4 – coal-rock sample; 5 – front amplifier; 6 – electromagnetic shielding net;
7 – acoustic-electric data acquisition system; 8 – pressure controlling system; 9 – shielding room

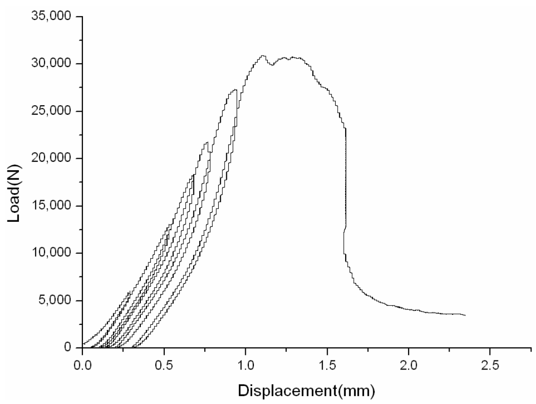
Fig. 2 Experiment system



(a) 1#



(b) 2#



(c) 3#

Fig. 3 Stress-displacement curves of coal sample $1^{\#}$~$3^{\#}$

and flatness. All the rock samples are mined from intensive drilling holes in the same roof rock, which guarantees the comparability of test results.

4.1.3 Experimental project

(1) Chose six coal samples according to criterion in 4.1.2 and number them 1#, 2#, 3#, 4#, 5#, 6#;

(2) Coal sample 1#, 2#, 3# are tested under uniaxial cyclic compression, controlling mode is displacement control with speed of 0.1 mm/min. When loading stress reaches 5kN, unload the loading stress to 0 and keep this state for 90 s (in order to eliminate the influence of former cycle) and go on reload. Stress peak values of following four cycles respectively are 10 kN, 15 kN, 20 kN and 25 kN. After all five loading cycles, make tested sample under compression with speed of 0.1 mm/min till completely fracture.

(3) Coal sample 4#, 5#, 6# are tested under uniaxial compression, controlling mode is displacement control with speed of 0.1 mm/min till completely fracture.

(4) In the loading and unloading process, the AE signals are collected by channel 2 and 6, their sensor resonant frequency are 51.76 KHz and 20 KHz. The AE sensor is joined with tested sample with paper scotch tape and vaseline is added between the sensor probe and the joint guaranteeing good coupling effect. To avoid the influence of end face, AE sensor is fixed away from the two end faces.

4.2 Experimental result and analysis

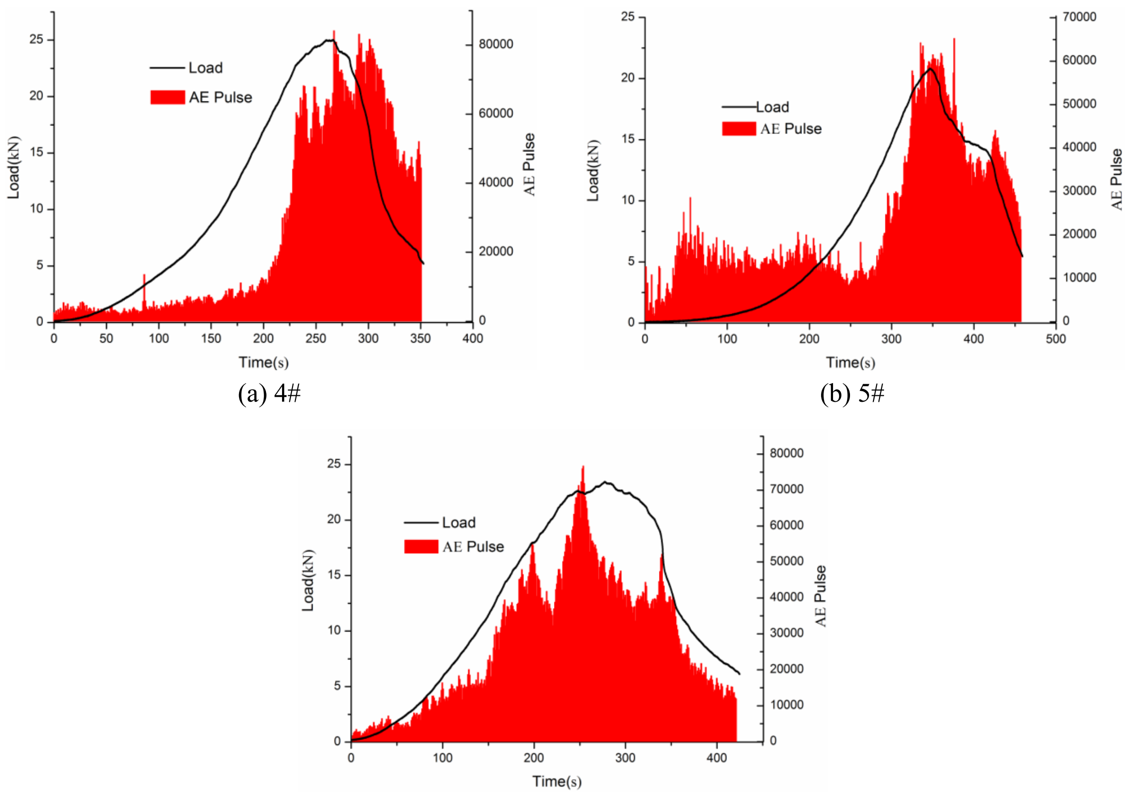
(1) Cyclic loading

Experimental results of cyclic loading and stress-displacement curves of coal sample $1^{\#}$~$3^{\#}$ are shown in Fig. 3. According to formula (1), unloading modulus E_U are calculated and shown in Table 1.

From calculate results in Table 1, unloading modulus of three samples all increase with loading

Table 1 unloading modulus of coal samples

Sample	Cycle times	σ (MPa)	ε_A-ε_C (%)	Unloading modulus E_U (MPa)	Average value E_U (MPa)	Total average value E_U (MPa)
1#	1	0~2.9	0.378	778	1280.8	1555.3
	2	0~6.4	0.6046	1054		
	3	0~9	0.693	1301		
	4	0~11.5	0.7567	1524		
	5	0~13.6	0.7758	1747		
2#	1	0~3.2	0.2648	1217	1658.8	
	2	0~6.5	0.4668	1392		
	3	0~9.6	0.5798	1655		
	4	0~11.8	0.6308	1867		
	5	0~14.5	0.6681	2163		
3#	1	0~3.07	0.2396	1281	1726.2	
	2	0~6.65	0.4406	1510		
	3	0~9.33	0.542	1721		
	4	0~11.1	0.5671	1957		
	5	0~13.9	0.6428	2162		



(a) 4# (b) 5#

(c) 6#

Fig. 4 stress-displacement curves and AE pulse diagram of coal sample $4^{\#}$~$6^{\#}$

stress rising because the sample' elastic modulus changes with the aggravation of damage during the cyclic loading process. The unloading modulus of tested samples is averaged in order to simplify the calculation process of plastic strain and eliminate errors caused by discreteness of tested coal samples.

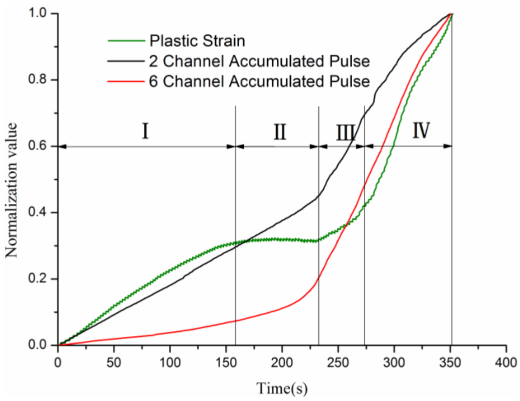
(2) Uniaxial loading

Experimental results of uniaxial loading are shown in Fig. 4. It is observed that, (1) There are AE signals emerging in the loading and compression process; (2) The AE pulse signal totally increases with the rising of loading stress and deformation speed. When it comes near the stress peak, the AE signal acts unusually and reaches its peak value nearby the stress peak.

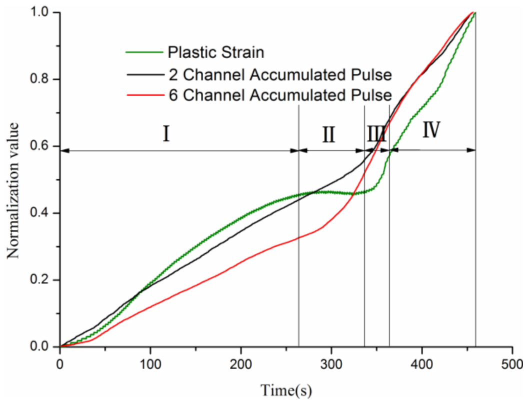
5. Relationship between AE and plastic strain

5.1 Loaded coal-rock AE feature parameter and plastic strain normalization

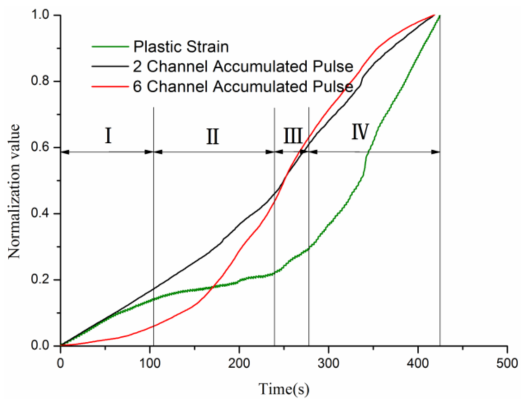
According to formula (2) and mechanical parameter calculation results of tested samples $4^{\#}$~$6^{\#}$, plastic strains of test samples are gained and their time corresponding curves are shown in Fig. 5. Only correspondence between plastic strain and AE pulse is considered here, so normalization of the tested data is made and shown in Fig. 5.



(a) 4#



(b) 5#



(c) 6#

Fig. 5 Summation curves of plastic strain and AE pulse of coal sample $4^{\#}$~$6^{\#}$

It is observed form Fig. 5, summation curves of plastic strain has high-positive correlation with that of AE pulse. Plastic strain curve in Fig. 5 accords well with the development laws of coal-rock elastic-plastic model:

(1) Densification stage (I): along with loading stress increasing, plastic strain and AE pulse accumulation keeps rising slowly and steady. The main reason is that large amounts of holes and cracks in original coal and rock mass turn to close under outside loading action. As coal strength is lower, part of coals near the crack start to have deformation and micro-fracture which leads to a certain of plastic strain. Meantime, elastic deformation also exists in this stage. There will be certain of elastic recovery after unloading.

(2) Apparent linear elastic deformation stage (II): plastic strain keeps unchanged while AE pulse increases slightly. It is because most reversible deformation and small portion of irreversible deformation contained at this stage. After unloading, most of the deformation will reverse remaining small part of residual, which means plastic strain exists. It is caused by slippage or breakage inside or between particles and dislocation has a great action in particle inside slippage. In fact, this stage is not a strictly speaking linear elastic deformation, so it is called apparent linear elastic deformation stage.

(3) Accelerated plastic deformation stage (III): plastic strain and AE pulse summation curves change from steady to sharply rising. After the apparent linear elastic deformation stage, certain density or amount of micro-cracks have formed in coal mass which lower coal bearing capacity. Coal and rock mass has accumulated enough energy which causes deformation acceleration, loading stress slowly rising and large amounts of micro-cracks joining and connecting. At this stage, especially the later stage, deformation always happens even under dead load, which is rheological phenomenon.
(4) Fracture and development stage (IV): plastic strain curve keeps rising heavily while AE curve slows down gradually. The main reason is that lager scales of cracks connect and cut-through with each other which lead to coal mass instability. The AE intensity reaches its peak at the final fracture moment and decreases after that.

5.2 Relationship between AE and plastic strain based on coal-rock damage theory

Under the action of outside loading stress and surrounding condition, the degradation destruction process of material or structure caused by micro-structural defect is defined as the damage (Yu and Feng 1997). According to continuum damage mechanics theory, damage fracture model can be established as formula (3)

$$\sigma = E(1-D)\varepsilon = (1-D)\sigma_e \tag{3}$$

Where E is elastic modulus; ε is strain; σ_e is effective stress; (1) $(1 - D)$ is effective stress-bearing relative area; D is damage parameter.

Under uniaxial compression condition, D denotes the ratio of micro-fracture (micro-hole or micro-defect) exists inside material volume element. $D = 0$ means intact material without any damage; $D = 1$ means volume element damaged.

Considering the influence of rock plastic deformation on theoretical model, the average elastic modulus is set as a constant, plastic strain is a variate and the elastic modulus is revised during the total process. The elastic modulus E is defined as

$$E = E_0\left(1-\frac{\varepsilon_P}{\varepsilon}\right) \tag{4}$$

In formula above, residual strength wasn't considered and based hypothesis "Weibull distribution" can't reflect rock residual strength feature. When $\varepsilon = \varepsilon_{\max}$, rock is regarded totally damaged and $D = 1$, conversed formula $\sigma = E\varepsilon(1 - D) = 0$ isn't coincide with reality. Thus, the residual strength is considered in this part and damage variable is revised as

$$D = D_U \times D' \tag{5}$$

Where, D_U is damage critical value, D' is damage parameter of different loading time, D is revised damage parameter of different loading time. With definition of residual strength, the damage critical value D_U is

$$D_U = 1-\frac{\sigma_C}{\sigma_P} \tag{6}$$

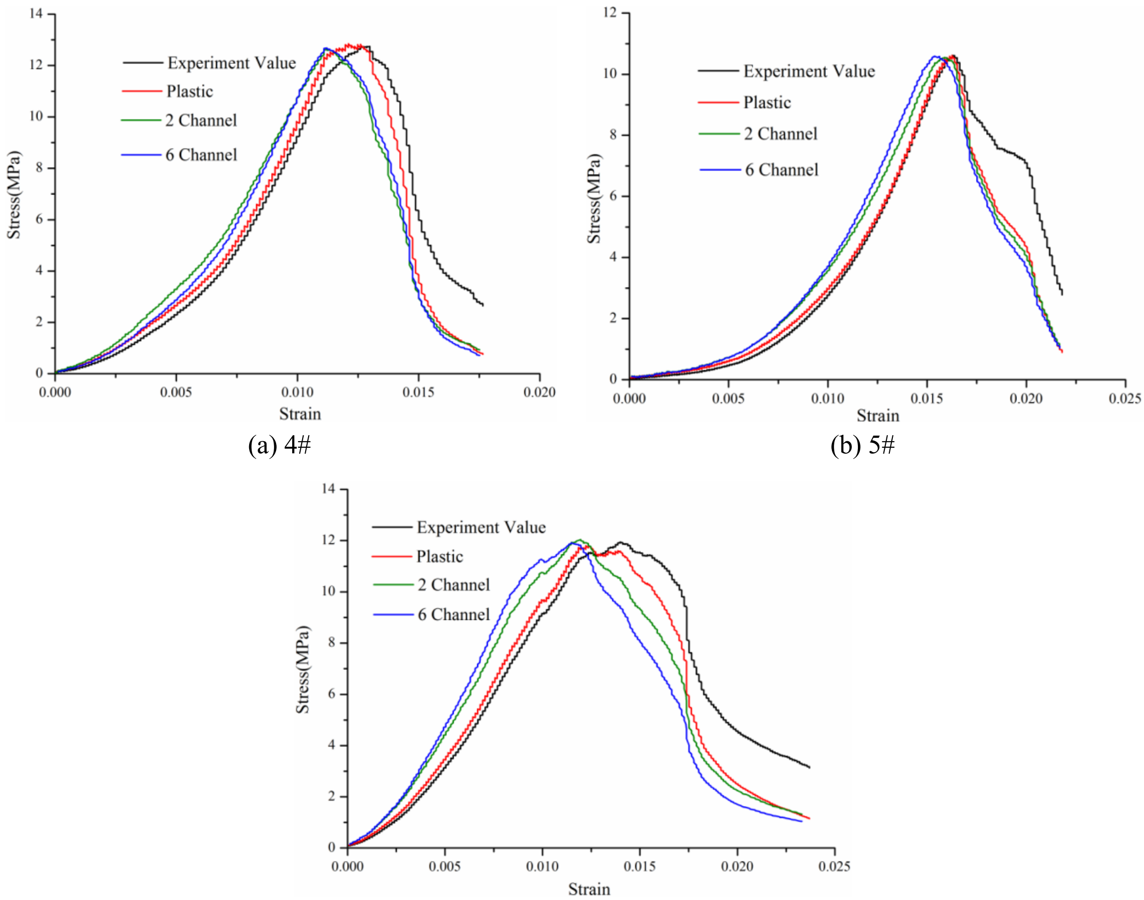
Where, σ_P is peak strength, σ_C is residual strength.

The damage constitutive model is established as

$$\sigma = \varepsilon E_0 \left(1 - \frac{\varepsilon_P}{\varepsilon}\right)\left(1 - \left(1 - \frac{\sigma_C}{\sigma_P}\right) D'\right) \tag{7}$$

By experimental results of the uniaxial compression, the "normalization" results of plastic strain and AE pulse accumulation are used as damage variate D' and taken into formula (7). The calculation results are shown in Fig. 6.

It is observed from Fig. 6 that (1) With considering of residual strength, taking the AE pulse accumulation and plastic strain as damage variate, the calculated stress-strain curves are all coincide with tested curves. The AE and plastic strain have coincident change and can reflect the damage revolution laws during the coal-rock loaded and damage process. (2) Comparison of curves in Fig. 6, we found that peak values of stress-strain curves calculated by the AE are all advancing than that of not only curves calculated by the plastic strain but also tested curves.



(a) 4# (b) 5#

(c) 6#

Fig. 6 Contrastive analysis of stress-strain curves

Therefore, the AE signal is surely advanced than plastic strain fitting peak and it is available to make forecasting of coal-rock dynamic disasters by taking the AE signal as forewarning information. (3) Compared with former researches, comparison error between theory curves and tested curves is smaller at densification and initial deformation phase, which indicates that the established damage constitutive model based on revising the elastic modulus with plastic strain is much coincident with actual coal-rock loaded and damaged process.

6. Conclusions

The high positive correlation between plastic strain of loaded coal-rock and AE (acoustic emission) characteristic parameter has been studied in this paper.

- Plastic strain of the whole coal-rock loaded and damaged process was obtained through experimental program in this paper. The coal-rock loaded and damaged process was divided into four phases with analysis of plastic strain curves' change laws: (1) densification stage; (2) apparent linear elastic deformation stage; (3) accelerated plastic deformation stage; (4) fracture and its development stage. It was coincident with coal-rock elastic-plastic model change laws.
- It was found that the AE curves rised with the plastic curves and had great correlation with them. It is an important basis for rock mechanical research and coal-rock dynamic disasters forecasting by using the AE technology.
- The theoretical curves of established damage constitutive model are relatively coincident with the tested curves. The peak values of AE signal are advanced than that of plastic strain fitting curves. The main reason is that the plastic strain and the AE correspond to different times during the coal-rock deformation and damage process. But both of the plastic strain and the AE can reflect the coal-rock loaded damage evolution law. Therefore, combining the AE and the plastic strain with coal-rock damage is feasibility and practicability for coal-rock dynamic disaster research.

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References

Aggelis, D.G., Verbruggen, S., Tsangouri, E., Tysmans, T. and Hemelrijck, D.V. (2016), "Monitoring the failure mechanisms of a reinforced concrete beam strengthened by textile reinforced cement using acoustic emission and digital image correlation", *Smart Struct. Syst., Int. J.*, **17**(1), 91-105

Cai, M.F. and Xiao, Y.B. (2006), "Law of deformation and failure of rocks surrounding reinforced roadway in complicated rockmass", *Metal Mine*, **3**, 29-31.

Cao, S.G., Liu, Y.B. and Zhang, L.Q. (2007), "Study on characteristics of acoustic emission outburst coal", *Chinese J. Rock Mech. Eng.*, **26**(S1), 2794-2799.

Fan, X.Q., Hu, S.W. and Liu, J. (2016), "Damage and fracture processes of concrete using Acoustic

Emission parameters", *Comput. Concrete*, *Int. J.*, **18**(2), 267-278.
Gao, B.B., Li, H.G., Li, H.M., Yuan, R.P. and Liu, Y.P. (2014), "Current situation of the study on acoustic emission and microseismic monitoring of coupling dynamic catastrophe for gas-filled coal-rock", *Progress Geophys*., **29**(2), 0689-0697.
Lai, Y.S., Xiong, Y. and Cheng, L.F. (2015), "Study of characteristics of acoustic emission during entire loading tests of concrete and its application", *J. Build. Mater*., **18**(3), 380-386.
Liu, B.X., Zhao, B.Y. and Jiang, Y.D. (2007), "Study of deformation-damage and acoustic emission character of coal rock under uniaxial compression", *Chinese J. Undergr. Space Eng*., **3**(4), 647-650.
Liu, Y.B., Cao, S.G., Li, Y., Guo, P. and Zhang, Z.G. (2012), "Correlation dimension analysis of AE sequence under failure process of gas-filled coal", *J. Chongqing Univ*., **35**(3), 108-114.
Liu, J., Wang, E.Y., Song, D.Z., Wang, S.H. and Niu, Y. (2015), "Effect of rock strength on failure mode and mechanical behavior of composite samples", *Arab. J. Geosci*., **8**(7), 4527-4539.
Masahiro, S., Hidekazu, S. and Masaru, S. (1988), "Hypocenter distributions of AE in coal under uniaxial compression", *J. Min. Metal. Inst. Japan*, **104**(1201), 163-168.
Nie, B.S., He, X.Q., Wang, E.Y., Liu, Z.T. and Sa, Z.Y. (2003), "Present situation and progress trend of prediction technology of coal and gas outburst", *China Safety Sci. J*., **13**(6), 40-43.
Satoshi, F. and Watanabe, Y. (1988), "Relation between bit diameter and activities during boring in coal seam: study on acoustic activity due to advance boring in coal seam", *J. Min. Metal. Inst. Japan*, **104**(1201).
Shi, X.X. and Li, H. (1998), "The prediction of coal and gas outburst using the acoustic emission technique", *Coal Geol. Explor*., **26**(3), 60-65.
Shkuratnil, V.L., Filimonov, Y.L. and Kuchurin, S.V. (2004), "Experimental investigations into acoustic emission in coal samples under uniaxial loading", *J. Min. Sci*., **40**(5), 458-464.
Tan, Y.L., Li, F.C., Zhou, H. and Han, X.J. (2007), "Analysis on acoustic emission pattern for gock burst", *Chinese J. Rock Mech. Eng*., **19**(4), 425-427.
Wang, E.Y., He, X.Q. and Liu, Z.T. (2004), "Study on frequency spectrum characteristics of acoustic emission in coal or rock deformation and fracture", *J. China Coal Soc*., **29**(3), 289-292.
Xiao, X.C., Zhu, H.W., Pan, Y.S., Xu, J., Luo, H. and Lu, X.F. (2013), "Acoustic emission warning signals change law research during deformation and failure of gassy coal rock", *China Safety Sci. J*., **23**(6), 122-127.
Yin, Y.Q. (1995), "On rock plasticity, damage and their constitutive formulation", *Scientia Geologica Sinica* (*Geological Sciences*), **30**(1), 63-70.
Yu, S.W. and Feng, X.Q. (1997), *Damage Mechanics*, Tsinghua University Press, Beijing, China.
Yuan, Z.M., Ma, Y.K. and He, Z.Y. (1984), *Acoustic Emission Technique and Application*, China Machine Press, Beijing, China.
Zhao, X.D., Li, Y.H. and Yuan, R.P. (2007), "Study on crack dynamic propagation process of rock samples based on acoustic emission location", *Chinese J. Rock Mech. Eng*., **26**(5), 944-950.
Zhou, F.X., Cheng, G.G., Wang, D.L. and Tong, Y. (2005), "The monitors and diagnoses system atic application study in earthquake and landslide based on acoustic emission technique", *Microcomput. Info*., **21**(10), 98-99.

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