Experimental Investigation on Influence Factors of Acoustic Emission Activity in Coal Failure Process

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Abstract: Stress-dominated coal and gas outburst disaster has become one of the main safety problems in deep coal mines. Acoustic emission (AE) or microseismic technology has been viewed as a promising method that can effectively reflect the stress and stability status of rock mass. The AE activity precursor of coal failure is the theoretical basis of this technology. In this study, AE experiments in failure process of coal specimens with different properties and under different stress conditions were performed in laboratory to explore influence factors and their effect of AE activity, and AE activity pattern classification was proposed based on the failure type of coal. The results indicate that the AE activity of different coals under loading are associated with the failure phase, and the evolution pattern of AE activity depends on the failure type of stressed coal. Both the mechanical property and the external stress condition have an important influential effect on the failure type and AE activity pattern in coal failure process. The internal mechanical property decides the inherent tendency of stressed coals to perform brittle or ductile behavior, and the responded AE activity pattern. The contrast of fissure distribution of specimens suggested that fissure structure in coal significantly affects the fracturing mode of coal in uniaxial compression and the AE activity pattern. The external stress condition has a transition effect on AE event energy distribution and AE activity pattern. Under the effect of external stress condition, the energy distribution of AE events was transforming between relative disperse and relative concentration, the failure type and AE activity evolution pattern of coal could appear the brittle-ductile transition. Based on the view of failure type, the pattern of AE activity of coal failure can be classified into three types, i.e., ductile, brittle, and semi-brittle pattern. It is suggested that the high-level AE activity can be viewed as the precursor of brittle instability of coal, and relative quiet phenomenon of AE activity as the precursor of ductile or semi-brittle instability. The research achievement can provide a theoretical base for the prewarning criteria establishment of coal and rock dynamic disasters at depth and improve the insight of AE activity in the coal failure process.

Keywords: acoustic emission; influence factor; coal; mechanical property; stress condition; laboratory experiment

1. Introduction

With the increasing of mining depth, coal and rock dynamic disasters, such as coal and gas outbursts and coal bumps are becoming more and more serious in deep coal mines, and have gradually

become one of the major problems restricting safety and efficiency of production in mines. Especially, the mechanism of coal and gas outbursts disaster at depth is more complicated than that in the shallow. Specifically, the effect of high ground stress becomes more dominant in hazard causing factors, and it leads to the frequent occurrence of coal and gas outburst in deep coal seams with lower gas content than in shallow [1]. The traditional outburst prediction approach, which mainly focuses on quantitative detection of methane in coal seams and provides a successful solution of outburst hazard prediction in shallow seams, has not been able to meet the demand of disaster prevention in deep mines because of its weakness in reflection on stress factors.

Acoustic emission (AE) technology is a prewarning method which can reflect the changes of rock mass stress and stability status [2–4]. Usually, there would be lots of AE signals that are emitted from coal or rock mass in the dynamic disasters development process. In engineering, AE technology has played an important role in risk assessment, prevention and control of rock bursts or roof falls in mines and excavation tunnels [5–7]. Meanwhile, some AE researches and applications on coal bumps [8–12] and gas outburst [13–15] prewarning have also been conducted in fields or laboratories. AE technology has become an important development direction of monitoring and prewarning method of stress-dominated coal or rock dynamic disasters at depth and has broad application prospects.

Obviously, the AE activity precursor and criteria model are the key of AE prewarning technology, and that have always been the focus of laboratory and field researches. The analysis of AE parameter series of rock failure and precursory information data mining of instability are the important methods of prewarning model establishment of rock mass instability or disasters. So far, the study of AE characteristics mainly focuses on occurrence frequency [16–19], energy [20–23], spatial distribution [24–26], source parameters [27–30], and modern mathematical analysis [31–37] of AE activity. Among them, AE occurrence frequency and energy characteristics analysis are the earliest analytical methods, and now are still the most important means of disaster prewarning analysis, in both situ AE monitoring without source location and microseismic (MS) monitoring application based on source location [9,10,29].

In AE activity researches, the early and most of laboratory studies of rock failure tests indicated that the AE activity of rock increases gradually with increasing loads. Hence, an anomalous high-level of AE activity was usually viewed as the signal of high stress state and instability risk of rock mass, some cases were also verified the correlation. For example, Mogi [16] found that the AE activity of loaded rock occurred in four modes with the loading process: weak, sporadic, or small, gradual increase with loads increase, with a sharp increase around main fracturing. In field monitoring, Nakajima [38] conducted the AE monitoring test of advanced borehole for stress releasing, and observed that AE activity in the stress relief zone was in lower level, while higher level in stress concentration zone. MS monitoring results [13] of gas outbursts in coal mines showed that MS activities were increasing continuously before hazard occurrence. Li [39] observed that the AE occurrence rate increased and was fluctuating at an abnormally high level before coal bumps. Zhang [25] found that coal bumps often occurred only in areas where the frequency of MS activity was active and the energy was high.

However, some experimental studies showed that AE activity decreased before failure of some coal and rock, and it is called a "relatively quiet period" phenomenon [19,40–45], which has been viewed as AE precursor of impending failure. Some field cases [46–51] also showed that the instability disaster of coal or rock mass occurred at the stage of AE activity decrease after rapid increase. Trombik [52] observed an increase followed by a decrease in MS activity preceding failure in many of the rock bursts that were occurring in a coal mine. Similarly, in Brady's investigation [53] of microseismicity associated with rock bursts, anomalous seismicity changes (increase followed by a decrease) were recorded prior to three moderate rock bursts. Wu [54] investigated the relationship between roof collapse and AE activity in iron mine, and found that roof collapse occurred during the decline stage of AE activity, and believed that the AE activity of rock burst induced by roof failure exists three stages: stable stage, active stage, and precursory stage. Zhao [55] observed that the frequency and energy of MS events decreased before rock burst. In the interpretation of the "relatively quiet period"

phenomenon, Brady [56] presented that the seismicity anomaly is associated with the formation of a primary inclusion zone. Xie [57] considered that the phenomenon is related to the absorption of strain energy in the process of damage zone healing.

Previous studies have shown that AE activity patterns of stressed coal and rock materials or dynamic disasters in different conditions, are diverse. The diversity of AE activity evolution patterns has caused great difficulty for the establishment of an effective AE prewarning model. Why do the differences exist? What are the main influence factors? What are the effects of factors? What is the key to classify the AE activity patterns of stressed coal?

As the condition of circumstance and rock property in every research is different, obviously, the internal and external influence factors of coal or rock failure is the key reason of the AE activity evolution diversity. Meanwhile, the failure of coal is the result of the joint effect of external stress and materials deformation, so all of the influence factors on failure process would have an effect on the AE activity. Some influence factors of AE activity and the failure of stressed coal or rock, such as heterogeneity [58–60], moisture content [15,61,62], gas [63,64], size [65,66], property [67,68], and loading condition [69–74] have also been studied in previous studies, and the results have indicated that each factor has its effect on the AE activity. However, the view and the focus of past researches were limited to the effect of each single factor. They have not explained why a "relatively quiet period" exists in some coals while others do not, and have not revealed the fundamental cause of AE activity pattern differences and the effect mechanism of influence factors.

In the paper, we conduct uniaxial compression tests of coal specimens with different properties and triaxial failure tests of coal under different stress paths, contrast the AE activity patterns of coals in different conditions, explore the key influence factors (mechanical property and stress condition) of AE activity and their effect, and discuss the classification of AE activity pattern of coal failure from the view of failure type. This has significant research value and practical implications for the analysis of rock mass stability and prewarning of mine dynamic disasters by AE technology.

2. Experimental Method

2.1. Coal Specimens

The test coal specimens are taken from seams of four coal mines with outburst risk or different bursting liabilities in China, and they are Yuyang mine (outburst risk), Pingdingshan 10 mine (weak bursting liability), Haishiwan mine, and Kouzidong mine (strong bursting liability), respectively. According to the standard of coal specimen making method, the specimens are cored from large coal blocks along vertical direction of bedding, then are polished to $\Phi50$ mm $\times$ 100 mm standard specimens, and of which, the non-parallelism are less than 0.05 mm, part coal specimens are shown as Figure 1.
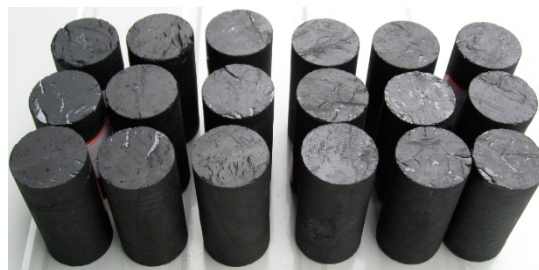

Figure 1. Photographs of part coal specimens.

2.2. Equipment

A computer-controlled rock test machine is used to carry out failure test of specimens. The AE equipment that was employed in this study, SAEU2S (Soundwel, Beijing, China), consists of two wide band piezoelectric sensors, two 40 dB amplifiers, and a two-channel data acquisition system.

The type of sensor is SR150N (Soundwel, Beijing, China) and the frequency response range is from 22 KHz to 220 KHz. The time parameters for AE signals definition, called Peak Definition Time (PDT), Hit Definition Time (HDT), and Hit Lock Time (HLT) are set to 150 μs, 300 μs, and 500 μs, respectively. The data sampling rate is set to 1MHz. The schematic diagram of uniaxial loading test and AE system is shown in Figure 2.
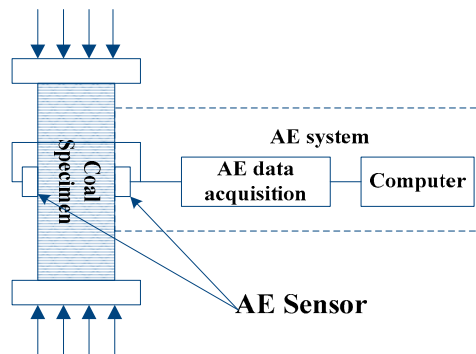

Figure 2. Schematic diagram of acoustic emission (AE) test system in laboratory.

2.3. Experiment Scheme

From the view of micro perspective, the failure process of stressed coal is the process of cracks initiation, propagation and coalescence in coal. AE is the elastic wave generated by the cracks development activity. Thus, the AE activity pattern should be closely related to the mode of cracks development in coal failure process. Because both are directly linked with material mechanical property and external stress condition. Therefore, in this paper, the internal property of coal and the external stress condition are taken as the influence factors to design the experimental study of AE activity.

The experiment is schemed to two parts: firstly, carry out uniaxial compression test of coal specimens with different properties, contrast AE activity patterns of each type of coal specimen, analyze the effect of mechanical property; and secondly, conduct failure test of coal in different stress paths (uniaxial, triaxial, unloading confining pressure), analyze the influence effect of external stress condition to failure mode and the AE activity pattern of coal.

According to test types of coal failure, the experiment can be divided into three kinds of tests, that is, uniaxial compression, triaxial compression under different confining pressure, and triaxial unloading confining pressure. The experimental scheme is summarized in Table 1.

(1) Uniaxial compression: The displacement control mode is adopted in uniaxial loading, stress coal specimen axially with loading rate of 0.005 mm/s to failure. During the test, two AE sensors are symmetrically attached on surface of coal specimen, and the sensors are glued with Vaseline at contact surface and fixed with adhesive tape. Axial loading and AE data acquisition are carried out simultaneously.

(2) Triaxial compression: Firstly, load confining pressure to specified value (5 MPa, 7.5 MPa, 10 MPa) and remain constant. Then, load axially under displacement control (loading rate of 0.005 mm/min) to specimen failure. During the test, two AE sensors are symmetrically arranged on the outer surface of triaxial chamber and fixed with adhesive tape. AE monitoring and axial loading are performed simultaneously.

(3) Triaxial unloading confining pressure: Firstly, load confining pressure to a specified value (5 Mpa). Secondly, keep confining pressure constant, and then load axially under displacement control to the value (30 Mpa) around 80% of peak strength at the confining pressure. Lastly, keep axial displacement fixed, and unload the confining pressure with a velocity 0.01 MPa/s until the failure of the specimen. AE monitoring method is the same with the triaxial compression.

Table 1. Experimental scheme of coal specimens test.

Specimen Number	Test Type	Confining Pressure/MPa	Property	Source
1			Outburst risk	Yuyang mine
2			Outburst risk	Yuyang mine
3			Strong bursting liability	Kouzidong mine
4	Uniaxial compression	/	Strong bursting liability	Kouzidong mine
5			Strong bursting liability	Haishiwan mine
6			Strong bursting liability	Haishiwan mine
7			Weak bursting liability	Pingdingshan 10 mine
8			Weak bursting liability	Pingdingshan 10 mine
9		5.00		
10	Triaxial compression	7.50	Weak bursting liability	Pingdingshan 10 mine
11		10.00		
12	Triaxial unloading confining pressure	5.00	Weak bursting liability	Pingdingshan 10 mine

2.4. Data Analysis Method

In the study, the occurrence frequency and the energy of AE signal are selected to be the analysis parameter. Specifically, according to time length of a single test of coal failure, AE Hit count in a second is chosen to be the calculation method of AE occurrence frequency, and energy accumulation in a second as the energy analysis approach to study the variation characteristics of AE activity in the coal failure process.

3. Experiment Result and Analysis

3.1. Result and Analysis of Uniaxial Compression Test of Coal with Different Property

According to test scheme (Table 1), eight uniaxial compression tests of coal specimens were carried out in laboratory. The temporal variation of stress, AE event rate, and energy of all the specimens are shown in Figure 3.

As can be seen from Figure 3, the AE hit rate and energy of specimens change along with the stress loading. Generally, the variation of AE activity characteristics is associated with the deformation phases that could be subdivided from coal failure process (take result of specimen S1 as example). In crack closure phase (I), only a small number of AE events occurred. In stable crack growth phase (II), AE hit and energy increased gradually with increasing stress. In unstable crack growth phase (III): AE hit and energy increased sharply and it achieved the maximum value in whole loading process when peak stress was reached. In post-peak phase (IV), stress gradually decreased with deformation increasing, and the overall declining trend of AE activity can be observed although sudden increase of AE hit might occur at points of stress sudden drop.

When contrasting the AE parameter evolution results of all the specimens, some differences in the AE activity evolution modes can be found among coals with different properties, although a similar feature also exists. For example, AE activity was increasing with the stress rise before peak strength. The evolutions of deformation phases and AE activity are different among the specimens with different mechanical properties. As shown in Figure 3a,b, in the post-peak phase, the stress drop of stress-strain curve is small and gentle, the variation of coal bearing capacity shows a gradual loss pattern. The failure process of outburst risk coal specimen is a progressive failure process. In post-peak phase, the stress drop of stress-strain curve is small and gentle, and the AE hit and energy decrease gradually. However, the strong bursting coal specimens (Figure 3c–f) exhibit a different response. The post-peak stage is extremely short, or even lacked, the drop of axial stress from peak to the final value is fast and sudden, and the AE activity, especially energy, bursts at the peak stress moment. The response of weak bursting coal specimens (Figure 3g,h) is somehow in between outburst risk and

strong bursting coals. The stress changes of weak bursting coal show a "sudden-gradual" alternating drop pattern, and the AE activity demonstrates a general relative rapid decrease trend with some pulsing AE events in the post-peak phase.

Therefore, generally, the AE activity evolution patterns in the failure process of coals with different properties, i.e., outburst risk, strong bursting liability, and weak bursting liability, can be described as stages shift of "activating—rapid increase—gradual decline", "activating-rapid increase", and "activating—rapid increase—decreasing with pulsing", respectively.

As "relatively quiet period" is concerned, we can find the phenomenon in AE activity response of coal specimens with outburst risk and weak bursting liability in post-peak phase, which cannot be observed in coal specimens with strong bursting liability. The AE activity decreasing mode is different between outburst risk specimens and weak bursting liability specimens. The AE decreasing mode is continuous for outburst risk coals in post-peak phase, and intermittent for weak bursting coals. Therefore, AE precursor of coal failure is related with the mechanical property of materials. The rapid increase of AE activity is the instability precursor for strong bursting liability coals under uniaxial loading, while AE activity declines after rapid increase for outburst risk coals.
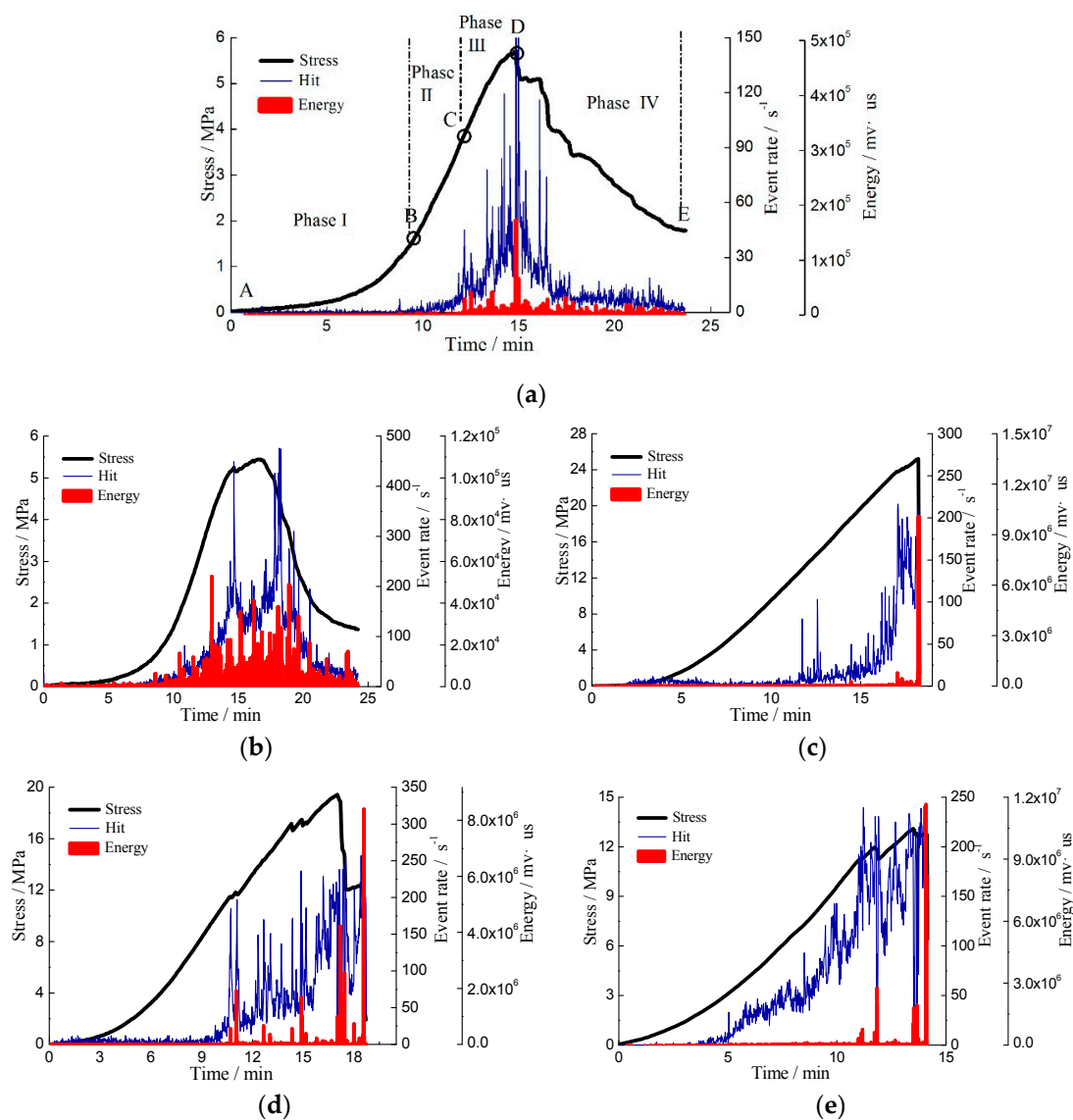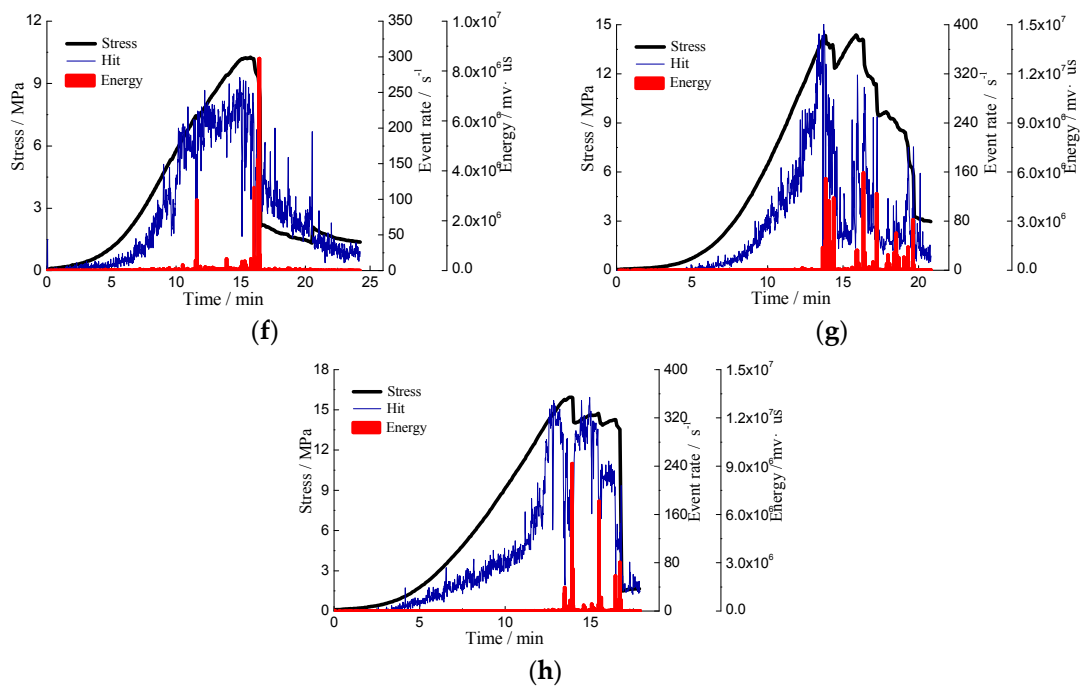

(**a**)

(**b**)

(**c**)

(**d**)

(**e**)

Figure 3. *Cont.*

Figure 3. Temporal variation of stress, AE rate, and energy rate of coal specimens. (**a**,**b**) outburst risk specimens from Yuyang mine: S1, S2. (**c**,**d**) strong bursting liability specimens from Kouzidong mine: S3, S4. (**e**,**f**) strong bursting liability specimens from Haishiwan mine: S5, S6. (**g**,**h**) weak bursting liability specimens from Pingdingshan 10 mine: S7–8. In figures, stress is denoted by thick black curves, AE hit rate by thin blue curve, and AE energy rate by red bar.

Since mechanical response of rock-like material is influenced by internal fissure structure [75–77], the fissure distribution feature of different specimens before test is contrasted by sectional pictures, as shown in Figure 4. It can be observed that, generally, the fissure distribution of outburst risk coal specimen is more abundant than weak or strong bursting coal specimen, and the strong bursting coal specimen is the least one. Fundamentally, AE activity is directly correlated with the micro-fracturing in the cracks development process. Obviously, the internal fissure structure will influence the crack development pattern of coals and AE response. In the failure process of the outburst coal specimen, the internal cracks propagation activity is mainly controlled by abundant fissures. When loading is increasing, the abundant pre-existing fissures would induce the nonuniform distribution of stress, that leads to the cracking activity increasing gradually, and the overall fracturing mode of coal failure is progressive. Therefore, the AE activity demonstrated an evolution pattern of gradual increasing before peak stress and gradual decreasing during post-peak. While fissure distribution of strong bursting coal is relatively less, the internal crack propagation mainly begins around peak stress. Thus, when the peak stress was reached, few cracks that control failure were formed and then rapidly developed to be macro-crack. It led to the overall fracturing process that can be characterized by a sharp sudden failure pattern, and AE activity increases sharply around the peak stress. The condition of weak bursting coal specimen was between the two, so the fracturing mode was between the sudden and the progressive one, and it led to the AE response of "activating—rapid increase—decreasing with pulsing". Therefore, the difference of AE activity pattern reflects essentially the difference in development mode of micro-cracking in coal failure process, and internal fissure distribution has an important influence on the fracturing mode of coal and AE activity pattern.
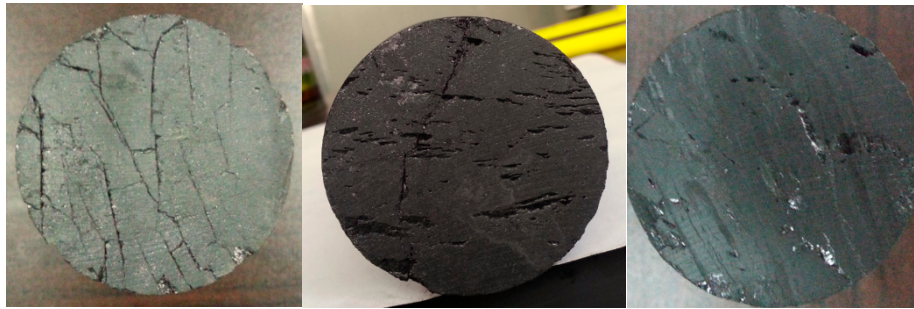
Figure 4. Photos of sectional fissure distribution of typical specimen before failure test. From left to right: specimen from outburst risk seam, weak bursting liability seam, strong bursting liability.

3.2. Result and Analysis of Coal Failure Test of Coal under Different Stress Conditions

According to test scheme, three conventional triaxial compression tests under different confining pressures (5 MPa, 7.5 MPa, and 10 MPa) and a triaxial unloading confining pressure test were carried out on weak bursting coal specimens S9–12. The temporal variation of stress, AE rate and energy of stressed specimens under different stress conditions are shown in Figure 5.
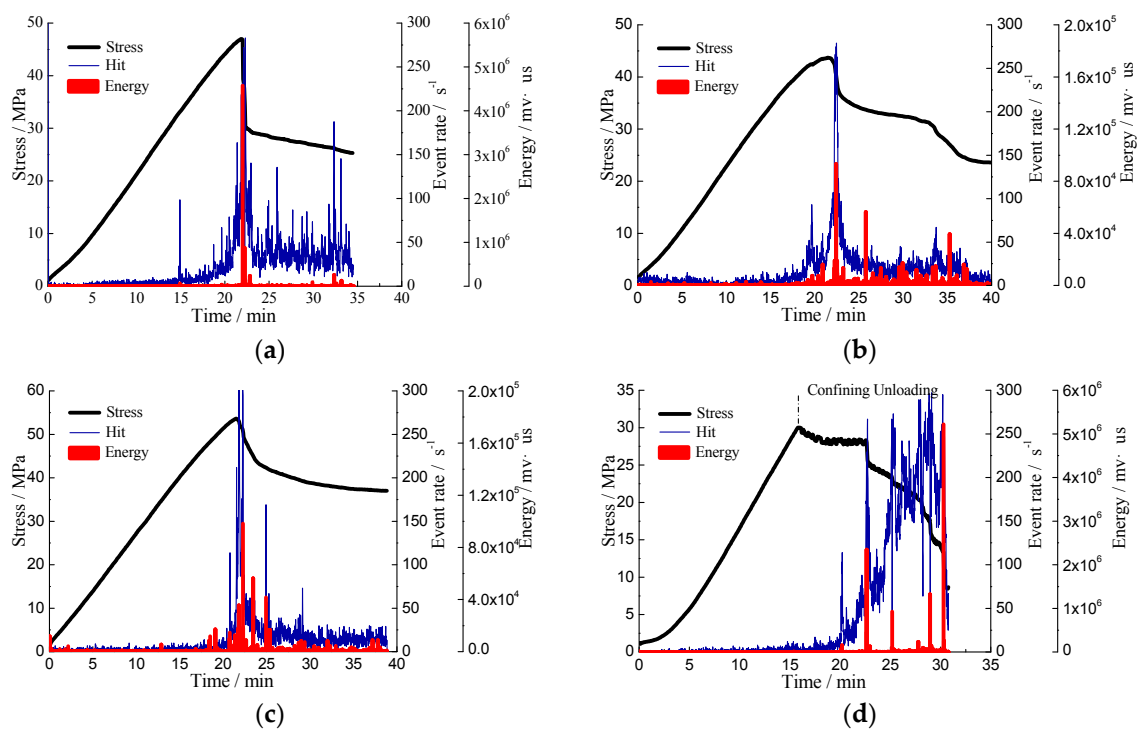

Figure 5. Test results of coal specimens under triaxial compression and confining pressure unloading. (**a**) 5 MPa confining pressure; (**b**) 7.5 MPa confining pressure; (**c**) 10 MPa confining pressure; (**d**) confining pressure unloading. In figures, stress is denoted by thick black curves, AE hit rate by thin blue curve, and AE energy rate by red bar.

The AE activity of coal specimens under triaxial compression also can be described by failure phases. As can be seen in Figure 5a–c, in the crack closure and the elastic deformation phase, the AE activity in the phase was not active because of the inactive micro-fracturing activity under the effect of confining pressure. In the yield deformation phase, the stress curve gradually deviated from straight line, and AE hit and energy increased rapidly and achieved the maximum value when the peak stress

was reached. In the post-peak phase, axial bearing strength of coal was gradually reduced, and the AE hit and energy gradually decreased.

As shown in Figure 5d, the AE activity in under triaxial unloading confining pressure test showed the following characteristics. In axial loading phase, the coal specimen was still in the state of elastic deformation, and AE activity was not active in the stage. In unloading, the beginning stage of confining pressure, the axial bearing capacity of specimen slowly reduced with the gradual decreasing of confining pressure, the AE hit began to increase gradually. It indicated that the coal body was gradually getting into the yielding stage. As the confining pressure continued to decrease, the axial stress of coal specimen that appeared suddenly dropped and then got into the rapid decreasing phase. Meanwhile, AE hit and energy soared and then got into a sharply active stage. It indicated that the damage rate of coal began to increase sharply and then went into the rapid failure stage.

With the contrast of AE activity distribution of the coal specimens under different confining pressure, it can be observed that the AE activity energy distribution of coal under 5 MPa confining pressure is mainly concentrated at the moment that peak stress is reached. The AE energy distribution of coal under higher confining pressure (10 MPa, 7.5 MPa) is more dispersed than that under low confining pressure (5 MPa). As listed in Table 2, with the confining pressure increase, the maximum and the mean energy value of AE event reduces. It indicates that the energy distribution of AE events was transforming from the relative disperse condition at a low confining pressure to the relative concentration condition at high confining pressure. The increasing confining pressure has an effect of transition from intensive fracturing to progressive fracturing.

Table 2. AE results of specimens under different stress condition.

Confining Pressure (MPa)	Maximum Event Rate (count·s^{-1})	Maximum Energy (mv·µs)	Mean Event Rate (count·s^{-1})	Mean Energy (mv·µs)
5.00	331	4.57×10^6	21.96	4.68×10^3
7.50	279	1.99×10^5	14.35	7.82×10^2
10.00	295	9.82×10^4	13.74	4.99×10^2
unloading	297	5.22×10^6	47.67	8.52×10^3

Meanwhile, when we compare the AE activity of a specimen under unloading confining pressure with that under triaxial compression, it can be found that both the maximum and mean energy of it are bigger than that in the triaxial compression tests. It indicates the failure mode of coal in unloading confining condition is more drastic than in triaxial compression. The confining pressure decrease has an opposite effect on coal failure mode and the AE activity to that of the confining pressure increasing.

Figure 6 shows the picture of failed specimens under different stress conditions. It can be observed that, with the increase of confining pressure, the main fracture angle to axial main stress direction is increasing, and in the confining unloading condition, the angle is far smaller than the triaxial condition. It indicates that the fracture mechanism of coal specimens was transforming under the effect of external stress.
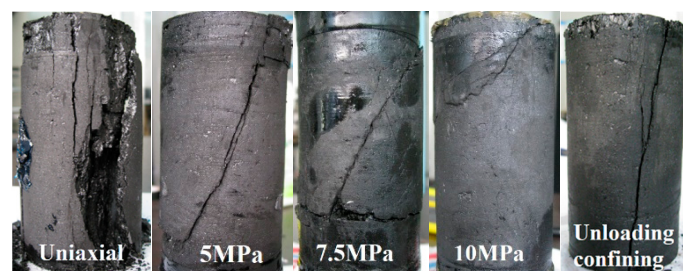

Figure 6. The main crack formation of weak liability coal under different stress conditions.

From the AE activity results of coal specimens under triaxial stress, we can find the "relatively quiet period" phenomenon in post-peak phase of weak bursting liability coal under triaxial compression, which demonstrates the continuous decreasing mode of AE activity, which is different with the intermittent mode when the specimen with the same property under uniaxial compression. However, when the specimen under confining pressure unloading condition, the phenomenon does not exist. Therefore, the "relatively quiet period" phenomenon of AE activity can be viewed as the instability precursor of coal under high triaxial stress condition, but cannot be viewed as that under the confining pressure unloading condition. It indicates that the AE precursor of coal failure is affected strongly by external stress condition. The change of external stress condition will lead to the change of AE activity pattern and the AE precursor.

4. Discussion

So far, a lot of experiments for AE activity characteristic of rock-like materials under various conditions have been carried out. However, most of them mainly focused on the AE characteristics, not the AE activity pattern differences in the coal failure process and the fundamental causes. From this study, we can find that both internal mechanical properties and the external stress condition of coal specimen have important influence on AE activity evolution pattern in coal failure process. Fundamentally, the AE event of coal rock mass failure is the elastic wave that is generated mainly by crack propagation. Meanwhile, the failure of coal is the process of cracks initiation, expansion, and coalescence in coal. Therefore, cracking activity mode is the key linking AE activity and failure process, the effect of internal mechanical properties, and external stress condition on AE is performed through their influence on cracking and failure mode. Thus, with the view of "failure modes" difference of coal materials, AE evolution pattern can be explained and classified, the effect of influence factors can be clarified.

According to the classification of failure modes of rock-like materials [78], the failure modes of coal can be classified into two types: brittle behavior and ductile behavior. For coals in this study, under uniaxial stress, the failure type of outburst risk coal can be viewed as ductile, that of strong bursting coal viewed as brittle type, and that of weak bursting coal is in between the two, can be called semi-brittle type. The typical stress curves of different type coals under a constant loading rate are shown in Figure 7. The failure mode of ductile behavior is progressive, while that of brittle behavior is sudden, and that of semi-brittle is "sudden-progressive" alternating in post-peak phase. It leads to the AE activity pattern difference of different coal specimens before instability. Therefore, the AE activity evolution pattern of coal failure can be classified into ductile, brittle, and semi-brittle pattern. The AE activity evolution of ductile pattern during coal during failure process can be described as stage shift of "activating—rapid increase—gradual decline". That of brittle pattern can be described as stage shift of "activating-rapid increase", lack of decreasing stage. That of the semi-brittle pattern can be described as stage shift of "activating—rapid increase—decreasing with pulsing".
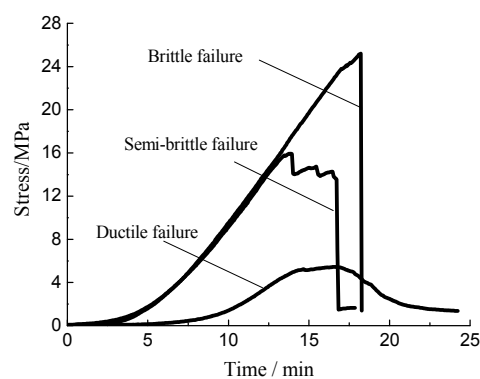

Figure 7. The typical stress curves of different failure types.

The internal property decides the inherent tendency of stressed coals to perform brittle or ductile behavior. Meanwhile, because the failure process is the joint effect of loadings and materials deformation, the external stress condition also has an important influential effect on the mechanical behavior of coals. In this study, it is observed that the behavior of weak bursting liability coal could be ductile in triaxial compression, also could be brittle in confining pressure unloading condition, and the AE activity pattern also changed along with failure behavior transition. Under the effect of external stress change, the failure type and the AE evolution pattern of coals can appear the brittle-ductile transition. With the increase of confining pressure, the failure behavior and the AE evolution pattern of coal specimen transform from the brittle to the ductile mode. On the contrary, with unloading of confining pressure, the failure behavior and AE evolution pattern transform from the ductile to the brittle mode. The corresponding experimental study [79] also indicated that rock appeared with more ductility and less brittleness in the failure process with the increase of confining pressure. At the same confining pressure, rock in the unloading confining condition presented the most brittleness and it reaches the highest broken degree. At depth, coal mass is usually in high, complex stress environment, the deformation behavior of coal becomes more complex than that in shallow. Therefore, under the complex stress and strong mining induced stress condition, the AE activity of coal instability in deep mine would be more complex. The analysis of effect of external stress on AE evolution pattern transition is of great significance for the prediction and the prevention of dynamic disasters in deep mines.

Generally, AE activity is directly associated with the amount of microcracks and the velocity of cracking propagation. The pattern of AE activity depends on the behavior of coal under loading, which can be defined by the failure type, i.e., ductile or brittle failure, and the behavior type is the macro response of cracking development (distribution, velocity, etc.) mode in micro perspective. With ductile behavior, cracks will usually propagate slowly and will cease when loading reduced. On the other hand, with brittle behavior, cracks spread rapidly and tend towards continuing growth once initiated. Under the effect of influence factors, the mode of cracking development changes, and fracturing behavior demonstrates the progressive or sudden mode in macro perspective, the responded AE activity shows the ductile or brittle pattern. Obviously, besides the fissure distribution and stress path of coal, other internal and external influence factors of failure behavior also include homogeneity, composition and structural characteristic, moisture content, stress path of loading, loading mode, stiffness of loading medium, etc. All of these influence factors would also affect the failure behavior and AE activity pattern of coal material, which should be considered in future study.

Concerning the relative quiet period phenomenon of AE activity before the instability of coal, some scholars have observed the phenomenon before dynamic disasters in geologic engineering and view it as a precursor of impending failure. While others have not noticed the phenomenon and view high-level (event count or energy) of AE activity as the precursor. From the experiment result in the paper, the reason of precursor diversity could be explained with the view of the failure type of materials. When the failure of coal mass is brittle behavior, instability happens after the high-level AE activity. While the failure of coal mass is ductile behavior, instability happens after the relative quiet period phenomenon of AE activity. As for the mechanism of the quiet phenomenon, because AE activity is the external behavior of the internal cracking activity, it is believed that the phenomenon is caused by the cracking cease in coal or rock mass. In addition, the intermittent quiet period is the external appearance of the cracking activity suspending with local stress adjustment in the semi-brittle failure process. Generally, the diversity of the AE precursor is the external illustration of cracks propagation mode difference in different type failure process.

In field AE monitoring, besides the influence factors that are discussed in the study, other factors that can affect the received AE signal, such as the monitoring technique or working procedure, should also be considered. For example, the signal attenuation that is caused by monitoring distance increasing could lead to the observed AE signal decreasing, which should be discriminated with the quiet period phenomenon. The stagnation of working operation or the stress relief of coal mass could also lead

to quietness of AE activity, which is different with the relatively quiet period that is discussed in this paper, and it does not mean the high risk of instability disaster. However, when the quietness after a high level AE activity occurs in the mining procedure, the cause of abnormal AE activity should be carefully analyzed for safety.

5. Conclusions

Acoustic emission technology is a method that could be applied in the monitoring and prewarning of coal or rock dynamic disasters in deep mines. The AE activity pattern in the failure process of stressed coals is the theoretical basis of this technology. AE experiments in the failure process of coal specimens with different properties and under different stress conditions were performed in laboratory to explore influence factors and their effect of AE activity, and AE activity pattern classification was discussed based on the failure type in this paper. Based on these studies, the following conclusions can be reached:

(1) The AE activity of different coals under loading are associated with the failure phase of coal in macroscopic, and the evolution pattern of AE activity depends on the failure type of stressed coal. Both the mechanical property and the external stress condition have important influence effect on the failure type and AE activity pattern in coal failure process.

(2) The internal mechanical property decides the inherent tendency of stressed coals to perform brittle or ductile behavior and the responded AE pattern. The contrast of fissure distribution of specimens suggested that fissure structure in coal significantly affects the fracturing mode of coal in uniaxial compression and AE activity pattern. Specifically, the failure type of coals with outburst risk, strong bursting liability, and weak bursting liability, can be defined as the ductile, brittle, and semi-brittle type, and their AE pattern can be described as stages shift of "activating-rapid increase-gradual decline", "activating-rapid increase", and "activating-rapid increase-decreasing with pulsing", respectively.

(3) The external stress condition has a transition effect on AE event energy distribution and AE activity pattern. With increasing of confining pressure, the energy distribution of AE events was transforming from relative disperse to relative concentration during the deformation process, and the maximum and mean energy value of AE event was reducing. On the contrary, the unloading of the confining pressure made AE hit, and energy soared and coal specimen went into rapid failure status. Under the effect of external stress condition, the energy distribution of AE events was transforming between relative disperse and relative concentration, the failure type and the AE activity evolution pattern of coal could appear in the brittle-ductile transition.

(4) Based on the understanding that AE activity is the external appearance of cracks propagation in coal, and the view of failure type of coal, the classification of AE activity pattern was proposed. The pattern of AE activity in coal failure process can be classified into three types, i.e., ductile, brittle, and semi-brittle pattern.

(5) The causes of AE precursor diversity and the relative quiet period phenomenon before coal or rock mass instability were discussed. Based on the classification of AE activity pattern, it is suggested that the high-level AE activity can be viewed as the precursor of brittle instability of coal, and relative quiet phenomenon of AE activity as the precursor of ductile or semi-brittle instability. Fundamentally, the AE quietness phenomenon is caused by the cease of cracking activity in coal or rock mass. The diversity of AE precursor is the external illustration of cracks propagation mode difference in the different type failure process of materials.

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