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Research On Failure Characteristics Of Coal Under Compression-Shear Load Based On Acoustic Emission

Danyang Xi[1], Jiankun Xu[2], Rui Zhou[3]
(School Of Resources And Geosciences, China University Of Mining And Technology, China)
(School Of Safety Engineering, China University Of Mining And Technology, China)
(Advanced Analysis And Computation Center, China University Of Mining And Technology, China)

Abstract:
In the compression-shear loading experiment of coal samples, the relationship between acoustic emission signals and sample failure process was analyzed from the time domain characteristics, frequency spectrum characteristics, and fracture component characteristics of acoustic emission signals. The experimental results show that during the compression-shear failure process of coal samples, tensile fracture occurs at the inflection point of the stress curve, while shear fracture occurs at multiple periods, with the most concentrated being the macroscopic failure of the sample. When the coal sample approaches failure, large-scale cracks expand, so that low-frequency acoustic emission events increase most significantly. After the coal sample is destroyed, apart from fracture along the shear plane, the areas of local peeling and large-scale collapse are mainly caused by tensile failure.
***Keyword**: Acoustic emission; Compression-shear load,; Fracture evolution; Failure mode.*

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I. Introduction

In coal mining, under the action of compression and shear, coal and rock mass often have a mixed failure mode of superposition of tensile stress and shear stress, such as changes in mine roof pressure [1], instability of roadway surrounding rock [2], development of water conducting fractures [3], etc. Compressive shear failure is the main form of coal rock mass failure. Through in-depth research on the characteristics of compression-shear failure of coal rock, the mechanical properties of coal rock mass under complex loads can be further revealed, which has important guiding significance for monitoring the stability of coal rock mass and ensuring mine safety production.

Acoustic emission(AE) is an effective way to monitor the process of rock failure [4], which can detect in real-time the elastic waves generated by micro fractures inside materials. By detecting, perceiving, and inverting acoustic emission signals, it is possible to achieve spatiotemporal localization of micro fractures and dynamically observe the evolution process of fractures [5,6]. The quantitative evaluation parameters of acoustic emission mainly include energy, count, amplitude, rise time, average frequency, etc. [7]. The study by Du et al. [8] showed that from the trend of changes in the number and energy characteristics of acoustic emission impacts, the rock fracture process exhibits a clear segmented variation characteristic, and rapidly increases before the fracture. The AE signals of tensile fracture and shear fracture have different characteristics for the fracture types of brittle materials such as coal. Usually, tensile fracture corresponds to AE signals with low RA and high AF values, while shear fracture corresponds to AE signals with high RA and low AF values [9]. Research has shown that tensile failure produces high-frequency signals, while shear failure produces low-frequency signals[11]. Wang et al.[12] found in their experiments that shear fracture and tensile fracture accompanied the entire process of rock damage and failure in Brazilian splitting tests and pre-set angle tests. The crack types reflected by the RA-AF distribution were consistent with theoretical analysis and actual failure results.

In this paper, through acoustic emission monitoring experiments of coal samples under compression shear loading, the relationship between the time-frequency characteristics of acoustic emission signals and the failure process and fracture morphology of coal samples was analyzed, providing a basis for quantitatively characterizing the failure mechanism and disaster evolution of coal rock mass under compression-shear loading.

II. Experimental Methods

The shear experiment of coal gangue samples was conducted by installing a variable angle shear fixture on the testing machine, as shown in Figure 1(a). AB is the shear plane, α is the shear angle, and the load

P can be decomposed into the normal stress σ perpendicular to the shear plane and the shear stress τ parallel to the shear plane. The loading speed is 0.2mm/min. When the load P exceeds the critical value, the specimen undergoes shear failure. The experiment used a 24 channel fully digital acoustic emission instrument, produced by Physical Acoustics Corporation (PAC) in the United States. The instrument parameters are set as follows: threshold value of 45dB, preamplifier of 40dB, peak definition time of 300μs. Eight acoustic emission sensors are arranged on two opposite sides of a 700mm × 700mm × 700mm cube specimen, as shown in Figure 1(b). The coal samples used in this study were taken from Baoli Coal Mine in Ordos City, Inner Mongolia Autonomous Region, China.

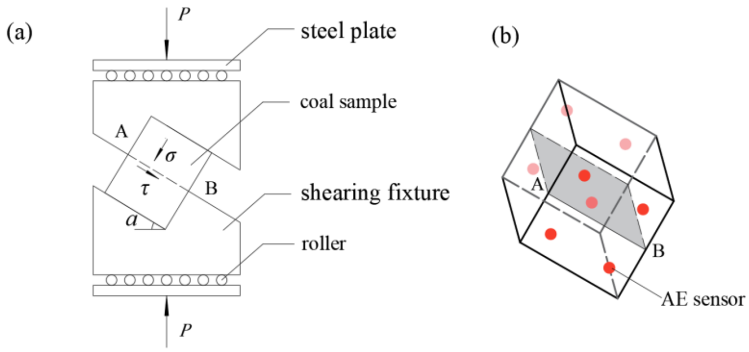

Figure 1: Schematic diagram of experimental method

III. Experimental Results

Time domain characteristics of AE signals

The acoustic emission and stress curves of coal samples are shown in Figure 2. Assuming the peak stress is P, five stress values of 10%P, 30%P, 60%P, 90%P, and 100%P are set, denoted as A, B, C, D, and E, respectively. In the stage before A, within 0-300s, the stress surface of the specimen gradually contacts and compacts with the testing machine, with slow stress growth and little acoustic emission activity; Within 300-800 seconds, the stress value increases and acoustic emission activity begins to be active. During the AC phase, the number of acoustic emission events significantly increases, and the energy of the events continues to rise, with a single peak in energy occurring between 1100 and 1200 seconds. In the CD stage, the stress value continues to increase linearly, but the acoustic emission activity significantly weakens compared to the previous stage, resulting in a "blank period". During this period, there are fewer micro rupture events, and a large amount of elastic energy accumulates inside the sample. This phenomenon is common on the eve of coal rock instability and failure. In the DE stage, the slope of the stress curve begins to decrease, and the cumulative number and energy of acoustic emission events rapidly increase in a short period of time until the peak value is reached when the E-point specimen undergoes shear failure.

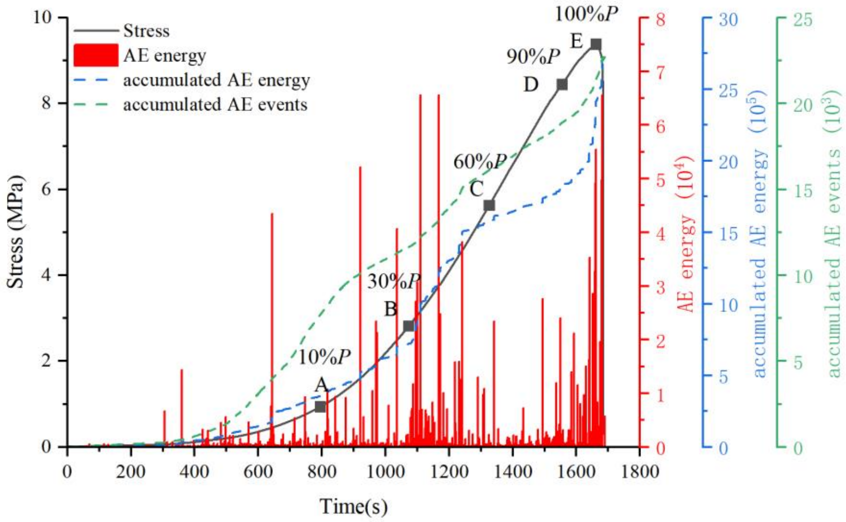

Figure 2: AE signals and stress curves

Spectral Characteristics of AE signals

The distribution of the main frequency of the acoustic emission signal in the time dimension is shown in Figure 3. The colors of the data points in the right figure represent the density of their occurrence in the figure, with red representing the densest and purple representing only one occurrence. Comparing the density distribution of data points in the frequency dimension, the main frequency of AE signals is mainly concentrated within 88kHz, with the most densely populated area around 25kHz, followed by around 50kHz. After 1600 seconds, the number of acoustic emission events in the 25kHz frequency band increased most significantly as the sample approached failure. There are two reasons for this: firstly, a penetrating crack is formed at this time, which hinders the propagation of acoustic emission signals, especially high-frequency components are more prone to attenuation; The second is the acoustic emission signal caused by the expansion of large cracks, with a more significant low-frequency component.

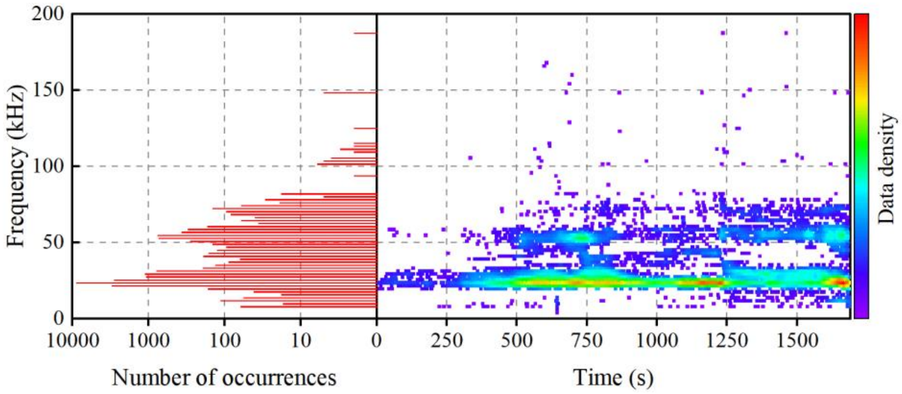

Figure 3: Frequency distribution of AE signals

Fracture characteristics

As shown in Figure 4(a), the relationship between AF value and RA value can be used to classify rock fracture types. The energy generated by tensile fractures in rock materials is mainly stored in longitudinal waves. Due to the faster propagation of longitudinal waves than transverse waves, the main energy (maximum amplitude) reaches earlier, resulting in a shorter rise time and therefore a smaller RA value (Figure 4b). In contrast, the energy generated by shear fractures is mainly stored in transverse waves, and the main energy (maximum amplitude) arrives much later, resulting in an increase in rise time and hence an increase in RA value (Figure4c). AF value has the physical meaning of average frequency; The signal frequency generated by tensile cracks is relatively high, while the signal generated by shear cracks is the opposite. The AE signals with high AF and low RA values represent the initiation and development of tensile fractures, while the AE signals with high RA and low AF values represent the initiation and development of shear fractures (Figure 4d). According to the ratio of AF/RA between two parameters, the changing trend of tensile and shear fracture components during rock deformation can be qualitatively characterized. When the AF/RA value is high, the sample is mainly subjected to tensile fracture, while when the AF/RA value is low, it is mainly subjected to shear fracture.

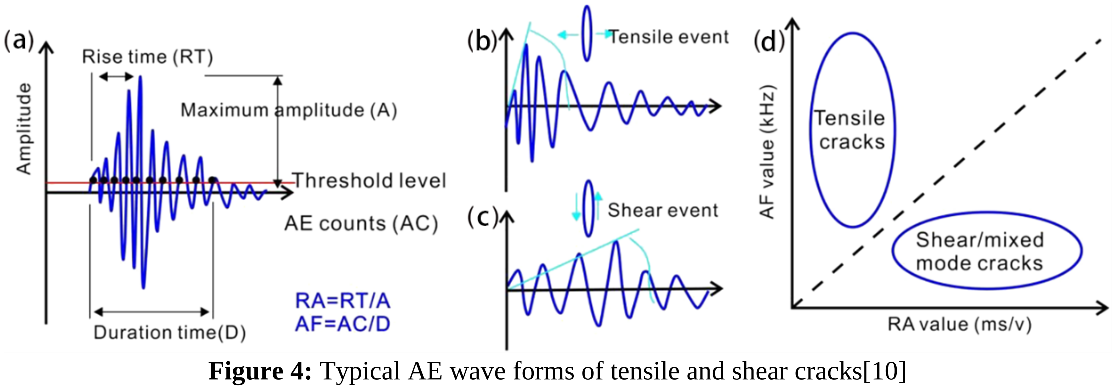

Figure 4: Typical AE wave forms of tensile and shear cracks[10]

The characteristics of AF/RA parameters are shown in Figure 5. The color scale represents the density of data points, the purple data points appear only once, and the red represents the highest density of data point positions (the AF/RA coordinate axis uses logarithmic coordinates). By comparing the AF/RA values with the stress curve, the stress values are very small and increase slowly during the initial loading stage (0~300s). At this stage, the number of acoustic emission events is relatively small and scattered, indicating that the sample is in the compaction stage and internal fractures occur less frequently; During the 300~500s stage, there is a significant increase in stress values, and acoustic emission activity begins to be active, indicating that the sample has fully contacted the testing machine pressure plate and small cracks continue to form inside; From 500~900s, the stress accelerates and reaches the turning point from nonlinear to linear growth, and the acoustic emission event points are relatively concentrated in region A; 900~1600s, the stress value increases linearly with time, and the acoustic emission event points are relatively concentrated in region B; After 1600s, the stress rapidly decreased after reaching its peak, and the specimen underwent shear failure. The acoustic emission activity was the strongest, and the event point was relatively concentrated in region C. The AF/RA ratios in regions A, B, and C where acoustic emission events occur are relatively small, indicating that the internal fracture of the specimens during these stages is dominated by shear stress; Acoustic emission events with an AF/RA ratio greater than 100 are most concentrated in the D stage, indicating that internal tensile fractures occur intensively during this stage.

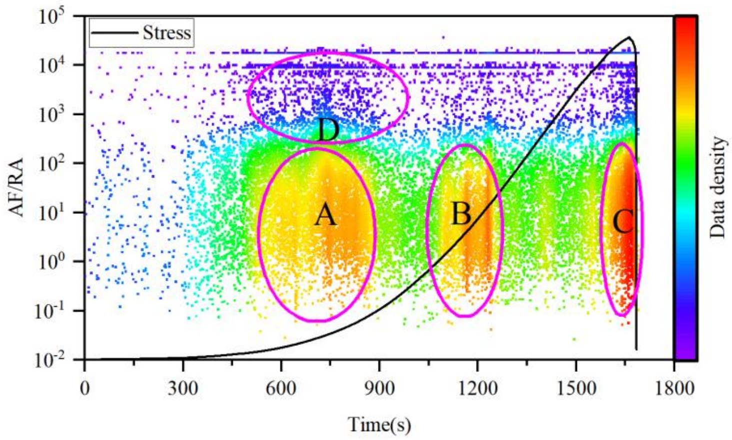

Figure 5: AF/RA characteristics of AE signals from coal samples

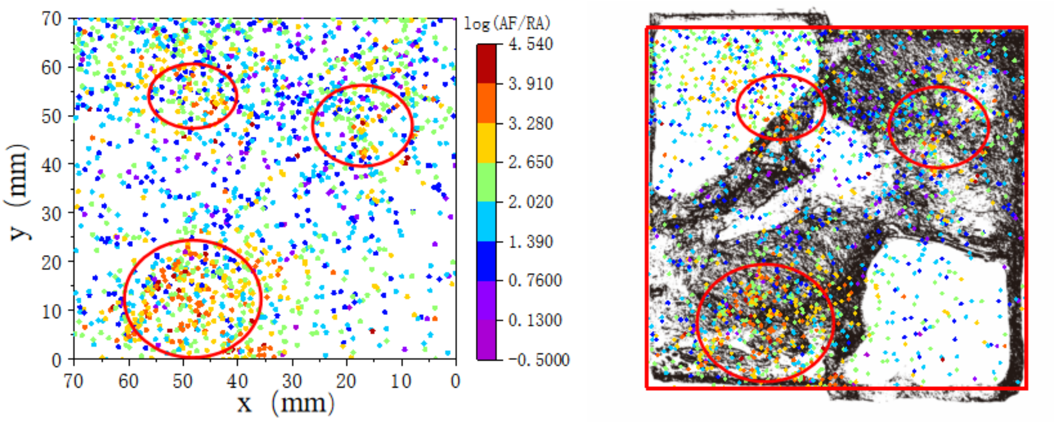

Figure 6: Comparison of projection of AE events localization points in coal samples

The shear failure mode of the coal sample and its comparison with the acoustic emission event location point are shown in Figure 6. The sample exhibits local peeling and large-scale collapse phenomena. The event locations with high AF/RA values are concentrated in areas of local peeling and large-scale collapse, indicating that the main form of fracture here is tensile fracture.

IV. Conclusion

(1) When the coal sample is close to failure, the penetrating cracks hinder the propagation of acoustic emission signals, especially high-frequency components are more prone to attenuation, and the number of acoustic emission events in the low-frequency band increases most significantly. In addition, the low-frequency components of the acoustic emission signals generated by the expansion of larger cracks are more significant.

(2) During the process of coal sample failure under shear force, the internal tensile fracture concentration occurs at the turning point of the stress time curve from nonlinear to linear growth, while the shear fracture concentration occurs at multiple time periods, with the most concentrated being when the sample is close to failure.
(3) After the coal sample is damaged by shear force, in addition to fracture along the shear plane, the areas of local peeling and large-scale collapse of the sample are mainly caused by tensile failure.

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