Failure behavior and acoustic emission characteristics of shale after subjection to high temperature

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Abstract: Uniaxial compression tests and acoustic emission (AE) monitoring on shale specimens with horizontal bedding planes and perpendicular bedding planes after subjection to high temperatures (25℃, 100℃, 150℃ and 200℃) were performed to investigate the effect of high-temperature environment on shale in rock engineering. Results show that specimens in the two bedding directions experienced severe rockburst failure, and the increasing temperature made rockburst failure more intense. The rockburst phenomena for all the specimens were similar and consistent, including spalling, particle ejection and block collapse. Temperature had no significant effect on the failure mode of specimens with perpendicular bedding planes, while specimens with horizontal bedding planes turned to splitting with the increasing temperature. Fractal dimension of fragmentation increased with the increasing temperature, and that for specimens with perpendicular bedding planes increased much more than that for specimens with horizontal bedding planes. Before the peak, the cumulative AE counts can be divided into three stages by stress level of 40% and 80%.

Keywords: Shale; High temperature; Failure behavior; Rockburst; Fractal dimension; AE

1. Introduction

Many major underground projects are located in shale, such as deep mining [1], shale gas extraction [2,3], and underground disposal of nuclear waste [4-7]. Generally, the temperature of rock stratum increases with the depth at a certain rate [8], which fully indicates that shale will inevitably be affected by the high temperature environment in relevant deep engineering projects. Therefore, it is necessary to perform laboratory tests on shale specimens subjected to high temperatures for its important engineering guiding significance.

At present, according to the exploratory experimental studies conducted by many scholars, there have been some rock mechanics understanding about the effect of high temperature on shale, such as Onishchenko et al. [9] performed a material composition balance analysis after high-temperature treatment of black shale and observed that the physical composition of this shale changed significantly.
Masri et al. [5] conducted uniaxial and triaxial compression tests on shale specimens with bedding planes inclinations of 0° and 90° after thermal treatment of 20°C-250°C. They found that with the increase of temperature, there was a significant decrease in Young's modulus and failure strength but an increase in the overall deformability of material as well as the nonlinearity of failure surface. Mohamadi and Wan [10] carried out a high-temperature triaxial compression test on shale specimens with a bedding plane inclination of 0° and found that both peak and post-peak strength envelopes were observed to be nonlinear with a pronounced curvature at low mean stresses which decreased at high temperatures. Meng et al. [11] carried out conventional triaxial compression tests on shale in high-temperature state and discovered that the different thermal expansivity of mineral particles might cause cross-grain boundary thermal expansion incongruity that created additional thermal stresses and reduced the bearing capacity of specimens. High temperature had significant effects on peak strength, cohesion and internal friction angle. Jha et al. [4,12] studied the effects of high temperature on the mechanical properties of two types of India shale and found that the uniaxial compressive strength and tensile strength of the two types of shale decreased with the increasing temperature, which varied in magnitude. Wang et al. [13] studied the anisotropic thermal cracks of oil shale under high-temperature triaxial stress, and noticed that thermal cracks occurred mainly along the bedding planes using X-ray computed tomography. Guo et al. [14] carried out uniaxial compression tests on shale specimens with five types of bedding plane inclinations after high-temperature treatment, and found that temperature had a great influence on the mechanical properties, such as elastic modulus, uniaxial compression strength and Poisson's ratio.

For all this, the studies reviewed above have not focused on evaluating the effect of high temperature on the failure process and characteristics. Moreover, the effect of high temperature on the acoustic emission (AE) characteristics of shale’s failure was not investigated in detail. Therefore, in this study, uniaxial compression tests on Longmaxi Formation shale after exposure to high temperature and AE monitoring assessment of the failure process were performed to deeply determine the effect of high temperature on shale. This study provides a theoretical basis for further research and presents useful information on deep shale rock engineering projects.

2. Materials and methods

2.1 Specimen preparation

The material studied in this paper is the upper segment of the Longmaxi Formation shale obtained from Changning County, Sichuan province, China. This material consists of organic matter, quartz, feldspar debris, clay minerals, carbonate and other minerals. The shale specimens with horizontal bedding planes and perpendicular bedding planes were drilled out from a single shale block, shown in Figure 1. According to the standards suggested by ISRM, all the machined cylindrical specimens with a length of 100 mm and diameter of 50 mm. After preparing the intact specimens, they were thermally treated using an electric resistance heating stove. To avoid thermal shock, they were heated at the rate of 2°C/min. Once reaching the predefined temperature, they were warmed for two hours to ensure that they were heated uniformly. When specimens were warmed for two hours, the power supply of the resistance furnace was turned off, and they were allowed to cool naturally to 25°C in the high-temperature closed furnace chamber. The temperature of specimens was categorised into four groups, namely 25°C, 100°C, 150°C, 200°C. Table 1 lists the parameters information of the tested specimens.
2.2 Test equipment

Uniaxial compression tests were carried out using an INSTRON 1346 electro-hydraulic servo loading system with a constant speed of 0.15 mm/min. Before applying the load, rigid metal plates were placed at the two ends of the specimen and a moderate amount of butter was coated at both ends of the rock and metal plate to reduce friction at the contact interface. The entire loading process was recorded simultaneously by a high-speed camera at a speed of 125 frames per second, and monitored using a PCI-2 acoustic emission monitoring system accompanied with two Nano 30 sensors. Two preposition gains of the AE monitoring system are 40 dB and the sampling frequency was 10Msps. Additionally, to avoid the noise generated by electricity or machines in the lab, a specified threshold value of 45dB was set.

3. Results and discussion

3.1 Rockburst failure

Figure 2 and 3 show the pictures recorded by the high-speed camera during the uniaxial compression tests. It can be seen that the failure phenomena of specimens in the two bedding directions were consistent, including spalling, particle ejection and block collapse. After treatment of the same temperature, the particle ejection distance of specimens in perpendicular bedding direction was much longer than that of specimens in horizontal bedding direction. For specimens in horizontal bedding direction, block collapse was more severe and usually did not occur along the bedding planes. Due to the failure accompanied by particle ejection and block collapse, rockburst may occur in shale engineering under an appropriate stress environment. To discuss the effect of high temperature on rockburst intensity of shale in the two bedding directions, we used the far-area ejection mass ratio proposed by Gong et al. [15] (referring to the mass ratio of ejection cuttings falling outside the pressure head range of the equipment and ejection cuttings falling outside the pad) to evaluate the rockburst tendency of specimens. Figure 4 shows the far-area ejection mass ratios and corresponding rockburst tendency grades of specimens in the two bedding directions at each temperature. As can be seen from figure 4, the far-area ejection mass ratio of specimens gradually increased with the increasing of temperature, and the rockburst tendency gradually strengthened. Specimen in the perpendicular
bedding direction had high rockburst tendency at each temperature, while specimen in the horizontal bedding direction had medium rockburst tendency at 25℃. Owing to the significant influence of high temperature on the rockburst intensity of shale, especially for specimens in the horizontal bedding direction, sufficient consideration should be given to disaster warning and stability control of deep shale engineering.

![Figure 2](image1.png)

**Figure 2.** Rockburst failure phenomena of specimens in horizontal bedding direction: (a) 25℃; (b) 200℃.

![Figure 3](image2.png)

**Figure 3.** Rockburst failure phenomena of specimen in perpendicular bedding direction: (a) 25℃; (b) 200℃.

![Figure 4](image3.png)

**Figure 4.** Rockburst tendency of specimens in the two bedding directions after subjection to high temperatures.

**Table 2.** Failure mode of specimens in the two bedding directions after subjection to high temperatures.

| Temperature (℃) | Horizontal bedding direction | Perpendicular bedding direction |
|-----------------|------------------------------|---------------------------------|
| 25              | Shear                        | Splitting                       |
| 100             | Splitting                    | Splitting                       |
| 150             | Splitting                    | Splitting                       |
| 200             | Splitting                    | Splitting                       |
Failure mode of rocks also plays an important role in rock mechanics. Generally, shear failure occurs when rock fail along a steep single or conjugate fracture plane, and splitting failure occurs when rocks fail into long slabs or prisms. Failure mode of each specimen have been classified according to the final macroscopic failure crack, and is given in Table 2. It can be seen that temperature has no significant effect on the failure modes of specimens in perpendicular bedding direction, while specimens in horizontal bedding direction turn to splitting failure with the increasing temperature.

3.2 Fractal characteristics
The debris produced from the rockburst failure of specimens in the two bedding directions were irregular, granular, blocky and plate-like, and were collected and screened using standard screens of 9.5, 4.75, 2.36, 1.18, 0.6 and 0.15mm diameters to analyze their sizes distribution. The mass of fragmentations for each specimen was weighed using a high-sensitivity electronic balance. Because of the self-similarity of rock fragments, the fractal method can be used for the statistical analysis of rock fragments, and the fractal dimension can reflect the statistical characteristics of rock fragments [16]. It is generally believed that specimens with large fractal dimensions have more fragments, smaller volume and higher degree of fragmentation than those with small fractal dimensions. In this study, the fractal dimension D of specimens was calculated by using Eqs (1) and (2) [17].

\[ D = 3 - b \]

\[ b = \frac{\log (M_r/M_0)}{L_{gr}} \]

where \( M_0 \) is the total mass of fragmentation, \( M_r \) is the mass of fragmentation whose particle diameter is less than the sieve diameter \( r \), and \( r \) is the equivalent particle size, i.e., the sieve diameter.

| Temperature (°C) | Horizontal bedding direction | Perpendicular bedding direction |
|------------------|-----------------------------|-------------------------------|
| 25               | 2.04                        | 1.85                          |
| 100              | 2.08                        | 1.98                          |
| 150              | 2.12                        | 2.15                          |
| 200              | 2.16                        | 2.26                          |

Table 3 shows the fractal dimensions of tested specimens. As the temperature increased, rockburst fractal dimension of specimens in the two bedding directions gradually increased. When the temperature was 200°C, the increasing amplitude for specimens with horizontal bedding planes and perpendicular bedding planes were 6.93% and 22.16%. Furthermore, the fragmentation degree of specimens with perpendicular bedding planes increased much more significantly with the increasing temperature than that of specimens with horizontal bedding planes.

3.3 AE characteristics
3.3.1 AE counts. The characteristic of AE signals during loading is commonly used to reflect the damage inside rocks. Figure 5 and 6 give the relationship between stress, AE counts and cumulative AE counts and loading time for each specimen. According to the figures, the overall trend of AE counts versus loading temperature for all the tested shale specimens is similar. Initially, few significant AE counts were recorded when specimens were in the stage of microcrack closure. In the elastic stage, each stress drop induced by spalling and particle ejection could lead to an instantaneous increase in AE counts. In the failure stage, each stress drop induced by post-peak progressive failure also could result in an instantaneous increase in AE counts when the temperature is below 200°C. The evolution trend of cumulative AE counts versus loading time presents a step-jump trend with the increasing temperature, which is closely related to the stress-drop induced by rockburst failure. Furthermore, the
step-jump trend of cumulative AE counts versus loading time become more obvious with the increasing temperature. It is worth noting that before the peak, specimens in the perpendicular bedding direction had a more obvious stepped increase trend than that in the horizontal bedding direction with the increasing temperature.

Figure 5. Plots of AE counts, cumulative AE counts, and stress against loading time of specimen in horizontal bedding direction after subjection to high temperatures: (a) 25°C; (b) 100°C; (c) 150°C; (d) 200°C.

Figure 6. Plots of AE counts, cumulative AE counts, and stress against loading time of specimen in perpendicular bedding direction after subjection to high temperatures: (a) 25°C; (b) 100°C; (c) 150°C; (d) 200°C.

3.3.2 AE evolution. The AE evolution level of specimens can reflect the mechanical behavior during
the entire loading process and reveal the failure characteristics. Figure 7 depicts the cumulative AE levels versus the stress levels at each temperature. From the slope of the curves, it can be concluded that the cumulative AE level can be divided into three stages by the stress level of 40% and 80%. The cumulative AE counts increased relatively smoothly in the first stage, quickly in the second stage, and explosively in the third stage. After high temperature treatment of 200°C, specimens in the two bedding directions had an AE evolution level around 100% at the peak, which significantly reduced the complexity of post-peak failure and was consistent with the grade of rockburst tendency.

![Figure 7. Evolution of cumulative AE counts of specimen in the two bedding directions versus stress level at each temperature: (a) specimens in horizontal bedding direction; (b) specimens in perpendicular bedding direction.](image)

4. Conclusions
Uniaxial compression tests and acoustic emission monitoring on shale specimens in the horizontal and perpendicular bedding directions after subjection to high temperatures were performed. The main conclusions are as follows:

1) Rockburst failure occurred in specimens in the two bedding plane directions and became more severe with the increasing temperature. The rockburst phenomena were consistent for specimens in the two bedding directions, including spalling, particle ejection and block collapse. Temperature has no significant effect on the failure modes of specimen in perpendicular bedding direction, while the specimens in horizontal bedding direction turn to splitting with the increasing temperature.

2) The fractal dimension of specimens in horizontal and perpendicular bedding directions both increased gradually with the increasing temperature. When the temperature was 200°C, the fractal dimension increased by 6.93% and 22.16% respectively. The fragmentation degree of the specimens with perpendicular bedding planes increased more significantly with temperature than those with horizontal bedding planes.

2) Stress drops in the elastic stage could lead to an instantaneous increase in AE counts. Relationship curves between cumulative AE counts and loading time present a step-jump trend with the increasing temperature for specimens in the two bedding directions. Before the peak, specimens in the perpendicular bedding direction have a more obvious stepped increase trend than that in the horizontal bedding direction with the increasing temperature. The AE evolution level can be divided into three stages by stress level at 40% and 80% for specimens in the two bedding directions.

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