Identifying critical failure information of thermal damaged sandstone through acoustic emission signal

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Abstract
The changes in the acoustic emission signals of sandstone after treatment at different high temperatures are examined in this study. The results show that there is a critical point on the cumulative energy curve of the acoustic emission signals (almost between 60 and 90% of the ratio of the loading time and the total loading time), which can be used to identify the failure of sandstone that has been damaged by exposure to a temperature of 900 °C. As the temperature increases, the position of the critical point gradually changes, which indicates that high temperatures increase the plasticity of rock, and this gradually reduces the brittleness. The changes in b-value of acoustic emission shows that the transition behavior of rock from brittleness to plasticity is more obvious at temperatures higher than 600 °C, and the large-scale microcracking takes place at that temperature range, which is the main reason for the weakening and brittleness and the strengthening of plasticity of the sandstone.

Keywords: acoustic emission, sandstone, thermal damage, critical information

1. Introduction
Under the effect of high temperatures, many physical–chemical reactions will occur in rock, such as mineral decomposition, melting, phase transformation and cracking, thus resulting in variations of the physical and mechanical properties, and causing potential hazards during rock engineering projects (Yang et al. 2014; Mahanta et al. 2016). For instance, if the rock is exposed to very high temperatures during underground tunnel work (i.e. following a fire disaster), the stability of the rock will be destroyed, which will make the tunnel unstable and even cause tunnel collapse both during and after construction (Kaiser & Cai 2012). Therefore, there is both practical significance and academic interest in identifying the critical information of rock failure under different levels of damage in rock engineering that takes place in high temperature environments.

According to the reported studies, the typical stress–strain curve of brittle rock under uniaxial compressive conditions has obvious segmentation characteristics (Yin et al. 2016), and the part before peak stress of samples can be divided into four stages (Sun et al. 2015): compaction stage, elastic stage, development of stable micro cracking stage and unstable propagation of micro cracking stage (see figure 2). The lower limit of the unstable propagation of micro cracking is usually called the yield point. When the stress exceeds the yield strength, the propagation of the crack changes from slow to rapid, thus resulting in rapid damage of the rock. Therefore, the yield point of stress is considered to coincide with the critical point that identifies the rapid development of cracking, which results in the severe disintegration of the rock. The yield point has an important role in monitoring rock deformation and rock failure. Therefore, many
researchers have studied the variation of the physical and mechanical parameters of rock after reaching the yield point (Su et al. 2015; Akdag et al. 2018), and found that the measured P-wave velocity and apparent resistivity rapidly decrease (Tian et al. 2012; Sengun 2014; Sun et al. 2017; Zhu et al. 2017), while the permeability, acoustic emission signals and strain greatly increase (Chaki et al. 2008; Guo et al. 2017). Their findings allow the failure of rocks to be monitored at room temperature. However, with the implementation of engineering work such as excavation in deep strata, more and more rock engineering projects have to address the effects of high temperature (Sirdesai et al. 2017), which means that it is important to have information on the early signs of rock failure after thermal damage.

In light of the need for retrieve of the early signs of rock failure after thermal damage, this paper discusses the variation of acoustic emission (AE) signals, which is a non-destructive method that detects low amplitude signals in solids during the uniaxial compression of red sandstone after exposure to different temperatures. A critical point is found, in which there is a change in the plotted cumulative energy of the AE signals, and most of the critical point falls between 60 and 90% of the ratio of the loading time and the total loading time. Therefore, a method based on the plotted AE cumulative energy count proves to be effective in finding information on the early signs of sandstone failure after thermal damage up to 900°C. The results can be used in the monitoring of rock engineering involving high temperature environment, and the precursor information of the failure of the thermal damaged rock can be identified by AE information.

2. Experimental material and testing procedure

2.1. Sample preparation

The sandstone samples were obtained from Jurassic strata of a mine in Shandong Province, China, and the average thickness of this stratum is about 100 m. The samples appeared to be red in color and homogeneous, the average bulk density was 2.39 g cm\(^{-3}\) and they were cut into the cylinders of \(\Phi 50 \times 100\) mm (diameter \(\times\) height). Six sets of samples (with two samples in each set) were heated to temperatures of 25, 200, 400, 600, 800 and 900°C, respectively. The X-ray diffraction test showed that feldspar, calcite, quartz and turbid zeolite are the main minerals found in the samples. From the appearance, the texture of the sample is relatively uniform, and there is no obvious bedding. Its microstructure is shown in figure 1a, which was taken by scanning electron microscope (SEM). The SEM image indicates that the sample with different sizes of mineral crystals belong to siltstone. The cement is argillaceous, and the mineral particles are cemented together by pore cementation. In the natural state, there are some small intergranular cracks inside the sample.

2.2. Testing instruments and procedures

The thermal testing was carried out in a high temperature furnace, and the heating process was divided in three phases: (i) the samples were heated at a constant rate (5°C min\(^{-1}\)) to the target temperature; (ii) the samples were kept in the furnace at the target temperature for 2 h to ensure uniform heating and (iii) the samples were cooled down to natural temperature also at a constant rate of 5°C min\(^{-1}\). After the samples cooled down, four AE probes were fixed onto the surface of each sample by using adhesive glue, and then unconfined uniaxial compression testing was carried out on the sample through a uniaxial loading machine. The loading process is controlled by stress and the loading rate is 0.8 kN s\(^{-1}\). The AE signals were collected during the entire loading process, and the data were automatically stored in a computer. The AE signals were studied to determine information on rock burst. During the sampling process, the threshold value of the AE signal was set to 45 dB. The amplitude range of the AE signals was between 45 and 100 dB, center frequency of the resonant sensor was 150 kHz, preamplifier gain was fixed at 40 dB and the sampling rate was 3 MHz. The counting error of the AE meter was 1% and the measured amplitude error was 2%.

3. Experimental results and discussion

The mechanical properties and AE signal of the specimens after different temperatures treatment were obtained from the AE tests during the uniaxial compression. The stress and strain curves of sandstone samples after heated by different temperatures were shown in figure 3, and this indicates that the stress and strain curve of the samples changes obviously with the change of heating temperature. First, the decreases of uniaxial compressive strength (UCS) and the increases of the peak strain of samples were obvious with the increase in heating temperature. Then, the local shape of the stress–strain curve also changed. For specimens at room temperature that were heated by 200°C, there were several stress drops on stress–strain curve during the loading process, which indicates that there was local failure in the specimen. The stress value of the specimen increased gradually after local failure, which indicates that the local failure does not make the specimen lose bearing capacity. With the heating temperature increase, the stress drop on the stress–strain curve decreased gradually and then disappeared. When the temperature reached 400°C, the stress drop on the stress and strain curve was reduced and no obvious stress drop could be observed in some samples. When the temperature exceeded 600°C, the stress drop on the stress–strain curve was basically not observed. Finally, the strain value corresponding to the upper limit of the compaction section of the stress–strain curve (point A in figure 2) increased gradually, and it is easy to judge the position of point A from the stress–strain...
Figure 1. SEM images of sandstone specimens before and after heating. (a) 25°C; (b) 200°C; (c) 400°C; (d) 600°C; (e) 800°C and (f) 900°C.

curve while the judgment of the stage division between point A and point D is difficult (other methods need to be used to identify).

Figure 4 shows the changes in the UCS, peak axial strain and elastic modulus of the samples exposed to different temperatures. Figure 4a shows that the UCS of the samples decreased gradually with the increase of temperature (the decrease trend is approximately linear), which indicates that the temperature was more sensitive to damage of the sample. The axial strain generally increased gradually with the
Figure 2. Typical stress and strain curve of rock before peak strength (O is the origin of coordinates, A is the upper limit point of compaction stage, B is the elastic limit point, C is the yield point and D is the peak strength point).

Figure 3. Stress and strain curves of sandstone samples subjected to different high temperatures. (a) 25, 200 and 400°C. (b) 600, 800 and 900°C.

Increase in temperature, as shown in figure 4b. The specific change is that the strain of the sample changed little before 200°C, increased gradually from 200 to 800°C and decreased again from 800 to 900°C. According to the relevant literature (Kong et al. 2016; Sun et al. 2017; Zhang et al. 2019), it was found that the internal melting phenomenon of some minerals and cement of sandstone is more obvious after 800°C, which can also be confirmed by figure 1f. The reason for the decrease of axial strain is that the heating process leads to the melting and recrystallization of some internal crystals, as the SEM images show in figure 1. After cooling, the brittleness of samples increased and the strain decreased. In addition, the variance of UCS and axial strain was analysed (as shown in figure 4c), and it was found that the temperature had a more significant effect on UCS. The variance of UCS increased gradually at 800°C and decreased rapidly between 800 and 900°C; the variance of axial strain changed little before 600°C, increased rapidly between 600 and 800°C and decreased rapidly between 800 and 900°C. The high temperature also had an important effect on elastic modulus of sandstone samples, as shown in figure 4d. The temperature node of elastic modulus change was similar to axial strain, which changed little before 200°C and decreased relatively quickly from 200 to 800°C, then increased slightly from 800 to 900°C. The changes in the peak stress, peak vertical strain and elastic modulus indicate that high temperatures have a great impact on the sandstone properties. The weakening of the strength indicates that the high temperature action damages the rock structure and reduces its bearing capacity. The increase of the strain indicates that the deformation ability of the sample is enhanced, and the rock failure needs to accumulate a bigger deformation.

The structure of rock is an important factor affecting its physical and mechanical properties, so the change characteristics of rock microstructure after different temperatures were also studied by SEM, as shown in figure 1. Note that there is no significant change in the microstructure of the sample before 400°C, but the crack gradually developed after 400°C. For example, when the temperature reached 600°C, the local connected intergranular cracks and small transgranular cracks, which lead to the damage of partial crystals, were observed (figure 1d). When the temperature increased to 800°C, the width and length of the cracks obviously increased and the connectivity was enhanced (figure 1e). At 900°C, the cement and some mineral crystals obviously melted, and the cooled melt filled the cracks, so the microstructure looked relatively flat at this time (figure 1f).

The aim of this paper is to determine whether there are critical thresholds in the failure process of rock after thermal damage. So, the synergetic relationship between stress and AE signal during loading was plotted, as shown in figure 5 and figure 6. Figure 5 indicates the AE count rate of the samples at different temperatures (the time ratio in the
Figure 4. Changes in UCS and peak strain of sandstone samples subjected to different high temperatures. (a) Changes in UCS. (b) Changes in axial strain responses to UCS. (c) The variance of UCS and axial strain. (d) Changes in elastic modulus.

The rupture in rock is essentially a release of energy, so it is very important to study the early signs of rock failure through the cumulative energy of AE (which can be calculated by using equation (2)). The variations in the cumulative

\[ \mu = \frac{t_i}{t_l} \]

where \( \mu \) is the time ratio, \( t_i \) is the loading time and \( t_l \) is the total loading time.

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energy of AE of the sandstone samples objected to different temperatures under uniaxial compression are shown in figure 5.

\[ N = \sum n_i \]  

where \( N \) is the cumulative energy of the AE, and \( n_i \) is the AE energy at time \( i \).

From figure 6a, it can be observed that there was an obvious critical point of change in the cumulative energy of the AE during the compression process of the sample under room temperature, which basically corresponds to the critical point of the change in AE count rate of the samples. Figure 6 parts b–f show the test results of AE on sandstone samples that were heated by 200, 400, 600, 800 and 900°C. In comparing the plotted cumulative energy of the AE of the sandstone samples before and after exposure to high temperatures, it can be observed that the overall changes in the curves are similar, but the changes in each phase are different.
According to the general changes in the plotted cumulative energy of the AE during the loading process, the cumulative energy of AE was divided into three phases:

(i) Phase 1 (A-B): there is a small increase in the cumulative energy (at the beginning of loading). The cumulative energy of AE shows a small rapid increase caused by the AE signals emitted during the initial compaction of the pores and cracks inside the sandstone samples, which corresponds to the compaction stage (OA) in figure 2. This increase is relatively small.

(ii) Phase 2 (B-C): quiet phase (during the loading process). The changes in the cumulative energy of the AE are very small, which mean that there is very low or no AE in the elastic and development of stable micro cracking stages, as concluded by many researchers (Yang et al.)

Figure 6. Relationship between acoustic emission signal and stress during uniaxial compression of red sandstone with temperature. (a) 25°C; (b) 200°C; (c) 400°C; (d) 600°C; (e) 800°C and (f) 900°C.
This phase corresponds to the AB and BC phase in figure 2.

(iii) Phase 3 ($C_c$D$_c$): rapid increase in the cumulative energy (end of the loading process). In this phase, the cumulative energy of the AE shows a sudden increase, which indicates that the sample has experienced severe internal damage, with the rapid development of cracks (which eventually results in the failure of the rock). This phase corresponds to the CD phase in figure 2, indicating that the loading pressure has exceeded the yield strength of the rock, causing the rapid cracking of the rock until rock failure.

From the details on the changes in the cumulative energy of the AE, it should be noted that the damage characteristics of sandstone under high temperatures are reflected in Phases 2 and 3. First, the position of the critical point of the cumulative energy of the AE changes with increases in heating temperature, as shown in figure 7. When the temperature is 800°C, the position of the critical point of change of the time ratio is increased from 63.7% at room temperature to 89.3%. The change in the position of the critical point shows that the high temperature causes some damage in the rock structure. Second, the shape of the cumulative energy curve after treatment at high temperatures (especially at temperatures higher than 400°C) fluctuates more than that at room temperature. This variation indicates that high temperatures increase the plasticity of rock, and gradually increase the ductility or reduce the brittleness. Moreover, this also indicates that the local fracture in the sample is also reduced, and the failure of the damaged sample tends to be gentler, which is not conducive to stress concentration. This is consistent with the results of brittle-plastic transition of rock after exposure to high temperatures in Sun et al. (2015).

Figure 7 shows the positions of critical point in AE count rates and cumulative energy curve of AE of rock samples subjected to different temperatures, note that the critical point of two kinds of AE signals is basically between 60 and 90% of time ratio, and the critical point position of AE count rates basically changes little with temperature, while the critical point position of cumulative energy increases gradually with temperature. In addition, the b-value of AE (in critical point) has been applied to validate the mechanical transformation of the rock, which can be calculated by using the Gutenberg–Richter relationship (Datt et al. 2015).

Increases in the b-value indicate that the proportion of small AE event is increased and the rock fracturing is dominated by small-scale micro cracking. A constant b-value shows that the different stages of micro cracking are relatively stable, while decreases in the b-value indicate that more AE have taken place, as well as larger scale micro cracking. As figure 8 shows, the b-value increases with the increase in experienced temperature.

This shows that temperatures have obvious impact on the brittle-plastic transition of sandstone, and greatly decrease the brittleness of the samples. At the same time, the failure of rock changes from large cracking to micro cracking, which can be verified by the change of the amount of stress drop in the stress and strain curve and the change of the shape of cumulative energy curve of AE. The increase rate of b-value after 600°C is smaller than that before 600°C, which indicates that the interaction between the cracks is obviously enhanced, the spatial distribution of the cracks is gradually ordered and the complexity of the internal structure is gradually reduced. According to previous studies, the damage after 600°C is greatly affected by quartz phase transformation and decomposition of partial mineral (i.e. laumonite) (Zhang et al. 2019).
This shows that the AE method is effective for monitoring the failure process and identifying the critical point of early signs of failure of sandstone when exposed to temperatures less than 900°C.

4. Conclusions

The dynamic rupturing process of sandstone after exposure to different temperatures is monitored by using the AE method and the changes in the AE count rate and cumulative energy of the AE are analysed. Based on the findings, the following conclusions are made:

(i) The plotted cumulative energy of AE of the red sandstone samples after exposure to high temperatures (25–900°C) during uniaxial compression can be divided into three stages, which correspond to the compaction, elastic and development of stable micro cracking, and unstable propagation of micro cracking in a typical stress–strain curve, respectively. The critical point in the plotted cumulative energy of AE can be regarded as precursor information of rock failure after thermal damage, which applies to sandstone up to 900°C.

(ii) Based on the b-value of AE, it is found that the brittle-plastic transition of rock is obvious to the thermal damaged samples, and large-scale micro cracking takes place in a rock subjected to a temperature higher than 600°C, which means that the brittleness of the sandstone is reduced and the ductility is increased.

(iii) At higher temperatures, the position of the critical point in the plotted cumulative energy of AE gradually changes, and the curve fluctuates, which indicate that high temperatures increase the plasticity of rock, and gradually increase the ductility or reduce the brittleness.

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