International Journal of Rock Mechanics & Mining Sciences 90 (2016) 43–52

Contents lists available at ScienceDirect

International Journal of Rock Mechanics Mining Sciences

journal homepage: www.elsevier.com/locate/ijrmms

Nonlinear characteristics of acoustic emissions during the deformation and fracture of sandstone subjected to thermal treatment

Biao Kong[a,b], Enyuan Wang[a,b,*], Zenghua Li[a,b], Xiaoran Wang[a,b], Liang Chen[a,b], Xiangguo Kong[a,b]

[a] Key Laboratory of Coal Methane and Fire Control, Ministry of Education, China University of Mining and Technology, Xuzhou 221116, China
[b] School of Safety Engineering, China University of Mining and Technology, Xuzhou, Jiangsu 221116, China

ARTICLE INFO

Keywords:
Sandstone
Thermal damage
Acoustic emission
R/S statistics analyze
Multi-fractal characteristics

1. Introduction

With increasing mining depth, there is a significant increase in engineering disasters (e.g., large deformation of surrounding rock and underground temperature increases).[1,2] It is well-known that temperatures are higher deeper underground. The geo-temperature gradient generally ranges from 30 to 50 ℃/km. Beyond the normal temperature environment, the mechanical and rock deformation properties vary greatly compared with those observed under normal environmental conditions. The compressive rock strength, elastic modulus, and wave velocity tend to decrease at higher temperatures.[3–6] Given the rise in problems associated with underground engineering, such as the poor availability of storage facilities for nuclear waste and radioactive materials,[7,8] the development of geothermal resources,[9] and the reconstruction of underground structures following fire accidents,[6,10] there is a need to consider the temperature effect on rock. However, few studies have analyzed rock deformation and fracture mechanisms following high-temperature treatments of rock materials. Understanding the process of rock deformation and fracture under different temperatures is critical for predicting and evaluating the temporal and spatial evolution of rock deformation and stability.

The acoustic emission (AE) technique has been widely used in underground engineering for the evaluation and monitoring of rock stability as well as for providing early warnings with regard to coal and rock dynamic disasters.[11–13] An AE signal is produced by the rapid release of energy due to the stress concentration in the coal rock mass.[14] AE waves are related to the deformation and fracture of rock, as they are produced by micro-ruptures of the rock.[15] High-temperature treatment causes thermal damage to the rock, which in turn leads to thermal cracking.[16–19] The internal minerals of the rocks experience thermal expansion and thermal deformation.[3,16] Both sandstone and granite have threshold temperatures for thermal cracking. AE signals are produced not only during the thermal cracking process of rock but also during rock deformation and rupture under loading conditions after high-temperature treatment. [16,20]

After high-temperature treatment, AE signals increase with increasing stress.[21] AE signals are closely related to rock deformation and fracture. AE signals contain large amounts of information in terms of the internal structure and crack evolution.[22] Therefore, by analyzing the characteristics of AE signals, it is possible to obtain the spatial-scale separation characteristics of the rock failure process. Using the AE data, we can further analyze the mechanism of deformation and fracture of rock, which helps to gather useful data for predicting rock stability.

AE signals produced following rock deformation and fracture at room temperature tend to show nonlinear characteristics.[23] R/S analysis is a form of the nonlinear scientific forecasting method,[24] which is useful for analyzing AE signals and obtaining correlations for the failure process of coal.[25] Fractal analysis indicated that the rock material consists of different portions, with each similar to the whole structure to some extent. Fractal analysis can quantitatively describe the overall degree of heterogeneity and irregularity. It has self-similarity and scale invariance. The fractal dimension of AE signals can predict the failure state of rock.[22] Through the multi-fractal

* Corresponding author at: School of Safety Engineering, China University of Mining and Technology, Xuzhou, Jiangsu, China.
E-mail address: weytop@263.net (E. Wang).

http://dx.doi.org/10.1016/j.ijrmms.2016.10.004
Received 20 January 2016; Received in revised form 15 June 2016; Accepted 19 October 2016

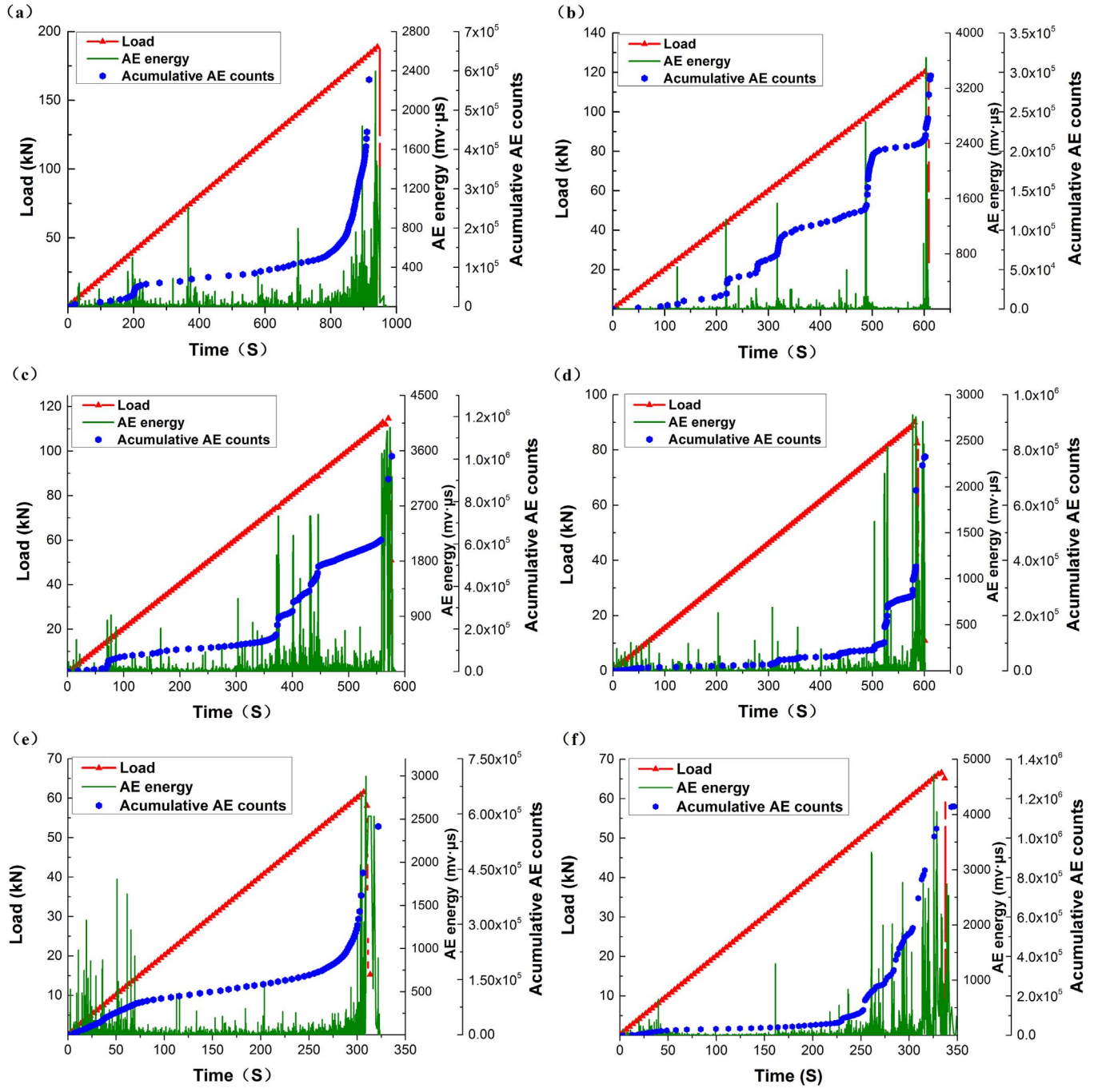

Fig. 1. Change characteristics of the AE signals (a) after 30 °C treatment; (b) after 200 °C treatment; (c) after 400 °C treatment; (d) after 600 °C treatment; (e) after 800 °C treatment; (f) after 1000 °C treatment.

analysis and deconstruction of AE signals, an inherent correlation can be identified between the AE signal scale separability and rock deformation.[23] Following high-temperature treatment, the internal physical structure and morphology of the rock structure changed.

In a previous study, the fractal dimension was used to evaluate the deformation and evolution of temperature-induced cracking in clays.[26] The crack distribution in oil shale specimens treated at temperatures between 200 and 600 °C showed fractal characteristics.[27] An analysis of rock fragments subjected to high-temperature treatment indicated that the limestone block distribution was related to the fractal dimension.[28] When the heating temperature increased, the fractal dimension of the fracture surface also showed an increasing trend.[29]

High temperature causes thermal damage to rocks; higher temperatures lead to a greater degree of thermal damage to rocks. Following treatment at different temperatures, AE waves showed significant differences in their characteristics during deformation and rupture. In particular, obvious differences were noted during rock deformation. Thus, an analysis of the AE wave characteristics following rock deformation and fracture is helpful to deeply evaluate the deformation and fracture mechanism of rock after high-temperature treatment. Sandstone is widely distributed in Chinese coal mines and in underground structures, and thus, it can be utilized to study the deformation and fracture of rock materials and their AE characteristics. In this study, the AE characteristics of sandstone deformation and fracture after high-temperature treatment are analyzed under uniaxial compression experiments. The AE time series characteristics of nonlinear characteristics, including the Hurst statistical law and multifractal characteristics, are studied.