International Journal of Mining Science and Technology 24 (2014) 819–823

Contents lists available at ScienceDirect

International Journal of Mining Science and Technology

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

Fractal characteristics of cracks and fragments generated in unloading rockburst tests

Li Dejian *, Zhao Fei, Zheng Maojiong

State Key Laboratory of GeoMechanics and Deep Underground Engineering, Beijing 100083, China
School of Civil Engineering, China University of Mining & Technology, Beijing 100083, China

ARTICLE INFO

Article history:
Received 5 February 2014
Received in revised form 7 April 2014
Accepted 17 June 2014
Available online 22 November 2014

Keywords:
Unloading rockburst test
Fragments
Grain distribution
Micro crack
Fractal dimension

ABSTRACT

True triaxial rockburst experiments with four different unloading rates were performed on four prism specimens of granite sampled from Beishan, China. The damage evolution in the rockburst test was investigated from two aspects including fracture surface crack and fragment characteristics. The scanning electron microscopy was used to observe the micro crack information on fragment surface. Combing binarization and box counting dimensions, the fractal dimensions of cracks were obtained. Meanwhile, the fragments were collected and a sieving experiment was conducted. We weighed the fragments qualities, counted the amount of fragments and measured the fragments length, width and thickness. Utilizing four methods to calculate damage fractal dimensions of fragments, the trend of fractal value changing with unloading rates can be roughly described. It can be concluded from these experiments that the fractal dimension either for crack or for fragment holds a decreasing trend with the decreasing unloading rate, indicating a reduction of damage level.

1. Introduction

Strain rockburst is one of the fracture types for rock mass during excavation. Due to numerous rapid fragments ejection and high energy release, rockburst plays a threatened role during geotechnical construction. Thus, the mechanism of rockburst needs a deep research from the viewpoints of theoretical and experimental analysis. Although much work has been done on laboratory study of rockburst, only the true-triaxial testing machine can truly simulate the stress conversion of rock mass during excavation [1–4].

It was introduced by Xie that the fractal theory can be used to characterize the geometrical features of rock fracture and rock crushing including micro and macro crack propagation and mass distribution [5]. It was found by Li et al. that the crack fractal dimensions were associated with stress state and rock mineral contents [6]. With fractal geometry and damage mechanics, the micro seismic induced by rockburst was analyzed to identify the seismic location by the correlation of fractal values and radius [7]. The fractal dimensions of fragments generated during rockburst tests were obtained by the correlations between the length and quantity, the width and quantity as well as the thickness and quantity [8]. It has been found that the crushing level and the flaky structure of fragments in rockburst are much more obvious compared with that in uniaxial and conventional triaxial compression test. After analyzing the fractal dimensions of sandstone fragments with different diameter ratios, it was concluded that the fragment grain is finer with increasing fractal dimensions [9]. It is commonly believed that rock fracture is a non-equilibrium process involving micro crack nucleation, formation and propagation. It was also found that fractal dimension is an important factor for determining rock brittleness [10]. Rock with lower fractal dimension is generally believed to be more brittle.

Up to date, little work has been done focusing on stress conversion of rock mass during rockburst under lab conditions and assessment of rock damage level by fractal theory, which is very important to understand the mechanism of rockburst. Consequently in the present paper the fractal behavior of rock in rockburst experiments by the true-triaxial testing machine was investigated for the evaluation of rock damage level. A series of rockburst tests were performed under different unloading rates to observe the process of rock damage.

2. Rockburst tests and results

2.1. Rock sample preparation

Tested granite samples were mined from Beishan, China, and the sampling depth is about 500 m. And the dimension for these specimens is 150 mm × 60 mm × 30 mm with the density of

* Corresponding author. Tel.:+86 13466736516.
E-mail address: lidj@cumtb.edu.cn (D. Li).

http://dx.doi.org/10.1016/j.ijmst.2014.10.014
2095-2686/

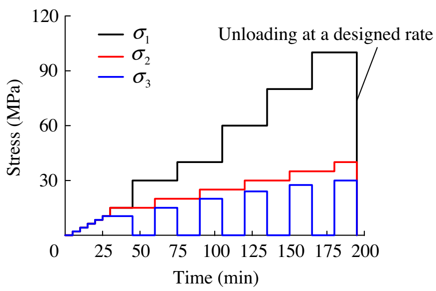


Fig. 1. Designed loading path for rockburst test.

2.6 g/cm^3. It was obtained by the X-ray diffraction analysis that the granite samples are mainly composed of 30.9% quartz, 13.5% K-feldspar, 27.0% plagioclase, 27.3% mica and 1.3% clay minerals. The uniaxial compressive strength is about 74 MPa and the samples are intact and compact with few pre-existing fractures. In addition, the P-wave velocities for these samples are all about 2000 m/s, indicating that these samples have a similar initial damage level.

2.2. Rockburst experiments

In this paper, the load-control system was utilized to apply load on rock specimen and the experiment has been introduced in Refs. [11,12]. Firstly, load the specimen in three directions to the initial stresses of $\sigma_1/\sigma_2/\sigma_3$ = 14/13/9 MPa and keep this state for about 30 min. Then, unload the minimum principal stress σ_3 to zero at the designed rate (20, 0.1, 0.05 and 0.025 MPa/s) and simultaneously add the maximum principal stress σ_1 to simulate the stress concentration during excavation. Maintain this fully unloaded state for 15 min and observe whether rockburst occurs. If there is not any change on rock specimen surface, the loading bar will be reinstalled to load σ_1 and σ_3. After 15 min, unload σ_3 at the designed rate and increase σ_1 to trigger rockburst occurrence. The loading and unloading process will not stop until the rock specimen fails at last. Fig. 1 shows the designed loading path for our study.

2.3. Test results

The rockburst test results are listed in Table 1 and it can be found that both the critical failure stresses and the failure duration have a decreasing trend with the decreasing of unloading rates. According to the description of failure process, it is readily concluded that the failure process is more dynamic with a higher unloading rate. With the lowest unloading rate, only flaky fragments splitting and falling down from the specimen can be observed.

3. Fractal feature of micro-cracks

3.1. Micro-cracks processing

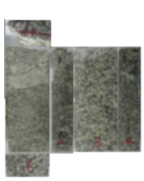
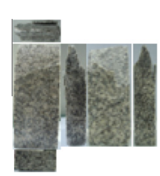
In order to obtain the fractal feature of micro-cracks on fragments, the scanning electron microscope experiments were performed on the typical fragments dropping down from the fracture surface and the SEM photos with 100 times magnification, which are presented in Fig. 2. Then, the photos' information can be clearly observed, including the crack morphology, crack size (length and width) and density as well as the fracture types such as transgranular fracture, intergranular fracture and mixed modes fracture. And binary image conversion with only two colors of black and white was applied to process these chosen photos. It is noted that since the SEM photos are actually grayscale images, only adjusting the photo brightness and contrast degree is enough for the binarization. The processing results for these four samples are shown in Fig. 2. It should be pointed out that only the crack information is retained and others are removed.

3.2. Fractal dimension calculation

Even if the area fraction of cracks enables to describe the crack development level on rock surface and its value is larger when the crack is developing, however, the crack area fraction cannot be fully used to characterize the crack distribution and growth level. These complex behaviors of cracks can be described by fractal theory, which has been demonstrated to be powerful to understand the dissipated process of crack propagation [13]. In this paper, the damage fractal dimension is applied to study crack growth.

The square grid with side length of L_0 is used to cover the crack binary image under a certain stress and then the side length of each small square in the grid can be written as L_0/n. Two factors for damage descriptions are the range of damage zone, which can be covered by the x–y grid and the level of damage, which can be represented by the amount of pixels in the damage zone. After counting the pixels in damage zone of each small square,

Table 1
Results of four unloading rockburst tests.

No.	#1	#2	#3	#4
Unloading rate (MPa/s)	20	0.1	0.05	0.025
Critical failure stresses $\sigma_1/\sigma_2/\sigma_3$ (MPa)	130.9/38.8/0.0	119.6/38.5/0.0	92.3/32.4/0.0	92.1/30.1/0.0
Duration of rockburst test (s)	36	30	23	17
Photos of fracture surfaces				
Description of failure process	Lots of small debris ejected quickly from the unloading surface. An obvious oblique crack run throughout from the middle to the top region with many flaky fragments dropping down. At last, the specimen has an entire destruction	Two macro inclined cracks joined each other and lots of rock flakes ejected from the top area. The rock mass in upper region fell down without causing heavy damage to the main rock body	Small debris ejected from the top region of surface. A big fragment fell along a macro transverse crack, which can be characterized by spalling damage	One crack developed clearly on the unloading surface. A piece of fragment bended and fell down along it. It exhibited no obvious dynamitic failure features