



Study on the Rock Damage Characteristics Based on SEM Test

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Abstract. The meso morphologies of the fracture surface of cracked rock mass indirectly reflects its internal damage evolution process. In this paper, the SEM scanning images of the specimens with different pre-existing cracks under uniaxial compression are post processed by MATLAB and IPP. Moreover, the damage evolution of meso structure in the failure process of the specimen is quantitatively studied, which establishes the relationship between macroscopic failure and meso mechanism. It is found that when the crack initiates, the damage degree of meso structure in the crack tips decreases with the increase of the inclination angle of pre-existing crack, and the weakening effect of tensile cracks on the strength of specimen is greater than that of shear cracks. Subsequently, when the crack propagates, the inclination angle of pre-existing crack has little influence on the damage rate of the meso structure.

Keywords: Damage evolution · SEM · Tensile and shear properties

1 Introduction

The meso structure of jointed rock mass will be damaged during the failure process under loading. With the accumulation of damage, the cracks will initiate, propagate, and coalesce the rock on the macro level. Thus, the study on the damage evolution law of meso structure inside the rock is of great importance. The conception of damage was first proposed by Kachanov [1] to study metal creep. On this basis, many scholars have studied the damage model of rock [2, 3], the meso morphology of fracture surface [4] and the fracture mechanism of rock mass [5] by conducting theoretical, experimental, and numerical methods. By comprehensive use of the theories of structure mechanics of rock mass, geometrical damage mechanics and rock fluid mechanics, the model of seepage-damage coupling was established by Zhao et al. [6]. Yang et al. [7] experimentally studied the deformation failure and energy properties of marble specimens under conventional triaxial compression. Wong [8] numerically studied the coalescence of two coplanar cracks in rock under compression using AUTODYN. These studies have comprehensively promoted the understanding of crack propagation process and failure evolution of rock mass. However, most of the researches are based on the microscopic mechanic properties of rock mass or the macroscopic crack propagation

process, and there is little quantitative study on the damage evolution of meso structure. Moreover, little attention has been paid to the research on the relationship between damage evolution of rock interior and macro mechanical property.

According to the previous study, the geometrical morphologies of crack fracture surface can be obtained by SEM. By comparing with the morphologies of pure tensile and pure shear specimens, the evolution pattern of the distribution of tensile and shear stress during the crack propagation process is analyzed [9]. In this paper, the SEM images of different specimens are post processed by binaryzation based on MATLAB in advance. Subsequently, the image analysis software Image-Pro Plus (IPP) is used to extract the data from SEM images after binaryzation, and these meso damage data are quantitatively analyzed. Finally, the damage evolution law of meso structure is summarized, and the relationship between the damage of meso structure and macroscopic crack propagation is established.

2 SEM Test

SEM is a microscopic observation method, which can directly scan the fracture surface of a specimen, as shown in Fig. 1. In order to obtain the criterion for judging tensile and shear cracks, the fracture surfaces of pure tensile and pure shear are manufactured artificially by Brazil splitting test and compression shear test. As shown in Fig. 2, under the action of pure tension, the typical fracture surface is rough and the meso-surface presents granular feeling. Under the pure shear, the typical fracture surface is smooth and the meso-surface presents friction sliding feeling [10]. On this basis, a weight parameter D is proposed for the analysis of tensile and shear properties of the crack propagation process and is defined as follows:

$$D = (A_s - A_t)/A \quad (1)$$

where A is the total area of the scanning section, A_s is the area with shear characteristics, A_t is the area with tensile characteristics. The range of D is $-1 \leq D \leq 1$, when $D = -1$, the section is pure tensile stress region, the new crack is tensile crack. When $D = 1$, the section is pure shear stress region, the new crack is shear crack.



Fig. 1. The schematic of SEM.

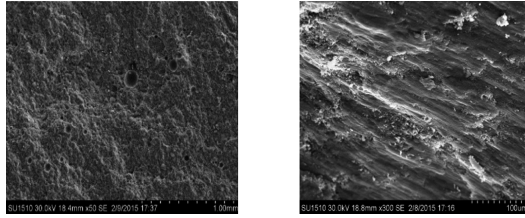


Fig. 2. Tensile (left) and shear (right) crack SEM images.

As shown in Fig. 3, the failure surface of the specimen was divided into three parts, and the SEM samples were selected from the corresponding areas [9]. Figure 4 shows the scanning images of initial stage, middle stage, and late stage of a 30° specimen. Observing the morphologies of fracture surface and the particle distribution at high magnification, the D values of the three stages are -0.8 , -0.7 , -0.4 , respectively [10].

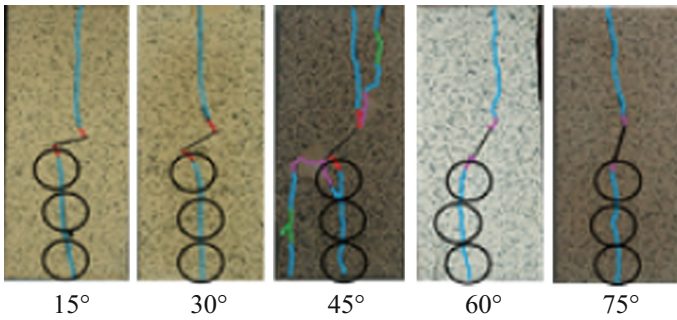


Fig. 3. Failure diagrams and sampling points of different specimens.

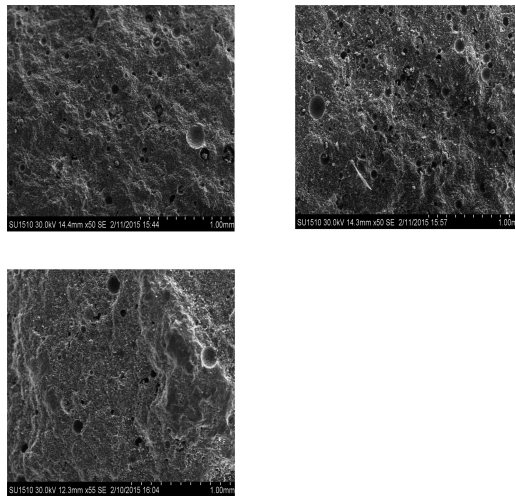


Fig. 4. SEM images of a 30° specimen.

It is found that tensile stress dominates the crack initiation and propagation of a 30° specimen. With the propagation of wing cracks, the weight of tensile stress decreases and the weight of shear stress increases gradually.

3 Post Processing of SEM Images

Based on the concept of validity [1], the ratio of the damaged area to the total area of the meso structure is taken as the meso damage variable. Therefore, the damage degree can be obtained by extracting damage area and total area from SEM images. The formula is as follows:

$$\Omega = \frac{S_e}{S_0} \quad (2)$$

where Ω is meso damage variable, S_e is the damage area, S_0 is the total area, the range of it is $0 \leq \Omega \leq 1$. When Ω is 0, there is no damage to the meso structure, when Ω is 1, the meso structure is completely damaged. According to the imaging principle of SEM, when the incident electron remains unchanged, the number of electrons reflected by rock crystal is more than that of the crystal void. On the macro level, the color of the undamaged area was shallow and the color of the damaged area was deeper. Using the threshold method, the SEM image with magnification of 300 times is transformed into binaryzation images. The images after binaryzation are shown in Table 1, the white parts represent the undamaged areas, and the black parts represent the damaged areas.

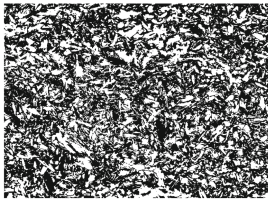
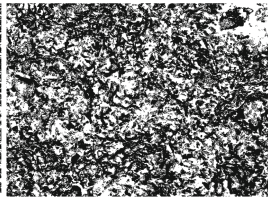
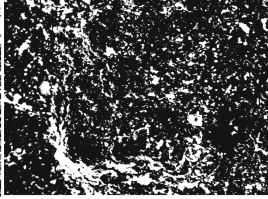
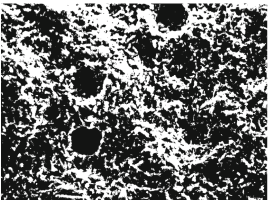
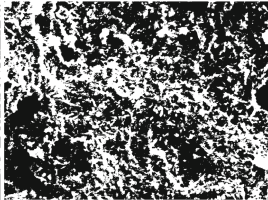
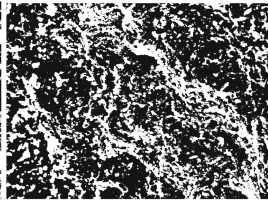
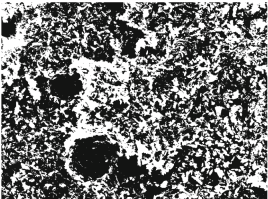
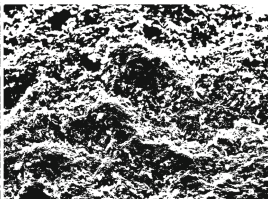
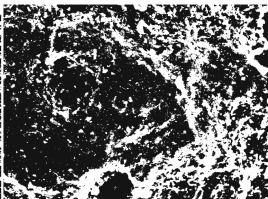
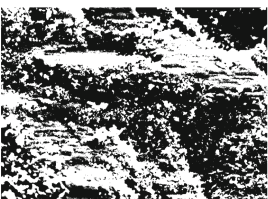
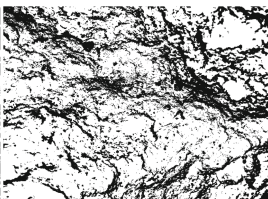
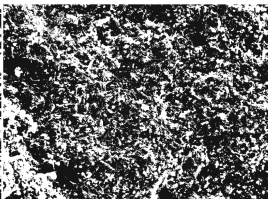
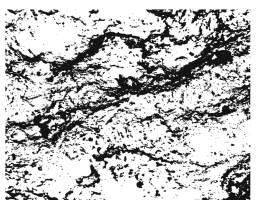
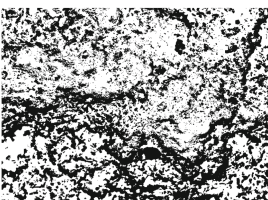
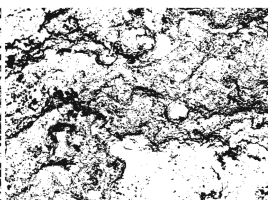
The graphic analysis software Image-Pro Plus(IPP)is used to analyze the binaryzation images, the amount of black and white pixels is extracted. Moreover, the value of Ω of crack initiation, crack propagation, and crack coalescence are obtained in Table 2.

4 Analysis of Meso Damage

Figure 5 presents the evolution curve of Ω at the initial stage with X axis representing inclination angles and Y axis the value of Ω . It is found that the damage degree Ω of the crack tips decreases gradually with the increase of the crack inclination angle. Zhao et al. [9] found that when the wing crack initiates, the proportion of tensile stress on the fracture surface decreases and the proportion of shear stress increases gradually with the increase of crack inclination angle. Based on the above analyses, a conclusion can be obtained as follows: With the increase of the shear stress on the crack surface, the damage degree Ω of the meso structure decreases gradually when crack initiates. That is to say, shear stress reduces the damage degree of meso structure when crack initiates.

Based on the previous study [11], Fig. 6 shows the initiation stress of different specimens in experimental tests and numerical simulation. Analyzing the curve of experimental tests, with the increase of inclination angle, the crack initiation stress increases gradually, indicating that the meso structure must have changed, which makes crack initiation more difficult to occur. This phenomenon also confirms the conclusion

Table 1. Binaryzation images of different specimens.

Inclination angle	Initial stage	Middle stage	Late stage
15°			
30°			
45°			
60°			
75°			

that damage proportion is getting smaller with the increase of inclination angle. However, when the inclination angles reach 60° and 75°, the crack initiation stress increases rapidly and has a multiple increase compared with other angles. The analysis of this particular case is as follows: In the case that the internal damage degree of the

Table 2. The value of Ω in different stages of different specimens.

Inclination angle	The value of Ω
15°	36.3%, 40.7%, 49.2% (initial stage, middle stage, late stage)
30°	36.1%, 38.4%, 47.2%
45°	34.8%, 41.6%, 45.5%
60°	32.5%, 36.0%, 43.7%
75°	28.3%, 32.0%, 41.0%

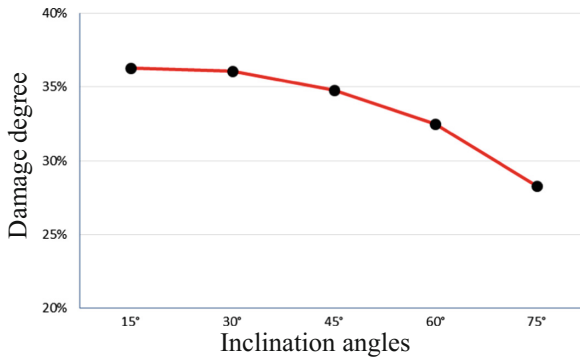


Fig. 5. The evolution curve of Ω at the initial stage.

specimens with different inclination angles is approximately uniform decreasing, the sudden change of crack initiation stress can only depends on the different weakening effect of tensile and shear cracks. When the inclination angles are 15°, 30°, and 45°, tensile crack dominates the crack initiation, when the inclination angles are 60° and 75°, shear crack dominates the crack initiation [9]. Therefore, it can be concluded that the weakening effect of tensile cracks on the strength of specimen is greater than that of shear cracks. Analyzing the curve of numerical simulation, it is found that there is no sudden change section in the stress curve, this is because numerical simulation does not take into account the different weakening effect between the tensile and shear cracks on the strength of the specimen.

Analyzing the variation of Ω from crack initiation to crack coalescence in Table 2, the five groups of data are 12.9%, 11.1%, 10.7%, 11.2%, and 12.7% respectively. It is found that although the damage degree of meso structure at crack initiation stage decreases gradually, the damage variation during the propagation process remains almost unchanged. Once the crack initiates, the tensile and shear stress on the fracture surface has little effect on the damage of meso structure.

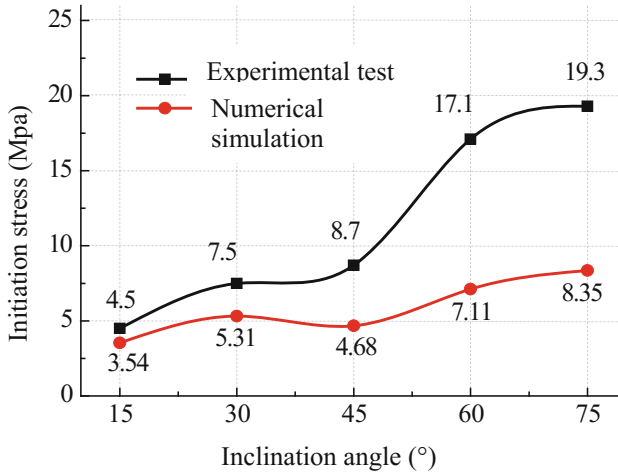


Fig. 6. Initiation stress of different specimens in experimental tests and numerical simulation.

5 Conclusion

In this paper, the SEM scanning images of the specimens with different pre-existing cracks under uniaxial compression are post processed by MATLAB and IPP. Moreover, the evolution of damage degree of meso structure in the failure process of the specimen is quantitatively studied, which establishes the relationship between macroscopic failure and meso mechanism. The conclusions are as follows:

- (1) When the crack initiates, the damage degree Ω of meso structure in the crack tips decreases with the increase of the inclination angle. Moreover, the weakening effect of tensile cracks on the strength of specimen is greater than that of shear cracks, which leads to the rapid increase of initiation stress of 60° and 75° specimen.
- (2) When the crack propagates, the inclination angle of pre-existing crack has little influence on the damage rate of the meso structure.

Disclosure statement

No potential conflict of interest was reported by the authors.

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