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Research Paper

Numerical study of crack propagation in an indented rock specimen

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A R T I C L E I N F O

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A B S T R A C T

Indentations were simulated to investigate the stress evolution characteristics of the indentation process using the discrete element method (DEM). The maximum principle stress and the shear stress were recorded by applying measurement circle logic. The results indicate that an increase in indentation force contributes to the concentration of shear and tensile stresses at the crack tips. The indentation force decreases because of the crack propagation, which is accompanied by stress dissipation at the crack tips. In addition, tensile and shear-tensile cracks, propagating in different modes, have been observed. The results show that the shear-tensile cracks are responsible for chip formation.

1. Introduction

Rock indentation is likely to cause rock breakage that affects indentation efficiency and tool wear. Thus, the rock breakage mechanism of indentation has been attracting interest for decades. Extensive investigations have contributed to the understanding of rock breakage by indentation. For example, Paul and Sikarshie proposed that rock fails because of concentrated shear force. They further stated that the slopes determined by the fluctuations in the indentation force and depth are constant [1]. In addition, Miller and Sikarshie proposed that tensile crack propagation is responsible for rock breakage due to indentation [2]. Considering the shear and tensile failure in the indentation process, the frequently used cavity model for a blunt indenter or a disc cutter demonstrates that a crushed core first forms because of the nonuniform contact force by the tool [3,4]. Then, a plastic zone forms around the core because of the compression induced by the crushed core. With further indentation, internal cracks initiate from the rim of this plastic zone [5]. The propagation and coalescence of these internal cracks determine the extent of chip formation between adjacent indentations. The indentation energy (characterized by the indentation force) and chipping volume (influenced by the propagation of cracks) codetermine the indentation efficiency. With respect to the characteristics of indentation forces, the laboratory tests of Chen and Labuz indicated that indentation force fluctuates with an increase in the indentation depth when the indentation depth is greater than a critical value [6]; recently, Yin et al. and Li et al. obtained similar results [7,8]. To obtain the crack propagation characteristics of the indentation process, acoustic emission (AE) events that reflect the extent of crack propagation were recorded by Yin et al. during biaxial indentation tests [7]. The increased AE counts at indentation depths greater than a critical value indicate that crack propagation also increases. In addition, Liu et al. and Entacher et al. proposed that the fluctuations in the cutting force are accompanied by a considerable increase in AE counts [9,10]. They concurred that the fluctuations of the indentation force are likely to be correlated with the crack propagation induced by the indentations. However, because of the ineffective observation of cracks in laboratory tests, the relation between force fluctuations and crack propagation is still an open topic.

Thus, numerical simulations, particularly those based on the discrete element method (DEM), have been widely used to investigate crack propagation during the indentation process. For example, Huang et al. proposed that tensile cracks initiate from the rim of the compressive zone and stated that the initiation point is influenced by the confinement [11]. According to the variation in the initiation points, they also classified cracks that were induced by indentation into vertical and lateral cracks. In addition, Ma et al. stated that indentation tests are capable of simulating linear cutting tests because indentation tests are conducted under a 2D plane strain condition [12]. They also observed fluctuations in the indentation force and AE events. Then, they measured the length and deflection angle of the crack to investigate the indentation efficiency. Additionally, a few other numerical studies investigated the initiation and connection of the internal cracks caused by indentations [13,14]. However, few studies investigated the dynamic evolution of the stress at crack tips after crack initiation, possibly correlative to the fluctuation in the indentation force.

The aforementioned studies agreed that tensile stress concentrations

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are responsible for chip formation. However, shear, tensile and shear-tensile cracks have been reported in rock and rock-like materials under different driving stress characteristics [15–19]. In addition, different confinements, joint distributions, and water contents are likely to result in a variation in the stress conditions and thus influence the crack pattern [20–24]. Nevertheless, few studies have investigated crack patterns produced during the indentation process.

Thus, in the present study, according to the simplification of stress conditions for rock breakage, a widely used DEM code, PFC 2D [25], was applied to investigate the dynamic stress evolution during the indentation process and to study the crack pattern of the internal cracks under a plane strain condition [12]. Considering the characteristics of indentation force, crack propagation energy, and recorded number of cracks, the stress concentrations and dissipations at the crack tips were discussed. In addition, to analyze the stress evolution characteristics in the chipping process, indentation simulations were conducted at higher confinements.

2. Numerical model and preparation

2.1. Brief introduction to PFC 2D and measurement circle logic

The Particle Flow Code in Two Dimensions (PFC 2D), which is an efficient and rigorous software, has been successfully used to simulate crack initiation, propagation, and coalescence in rock and rock-like specimens [15,25]. The PFC 2D model consists of particles, bonds, and walls. The geometry and mechanical properties of these elements can be predetermined. Bonds, divided into contact and parallel bonds, mainly determine the failure characteristics of the model. In natural rock, shear, tensile, and bending stresses are likely to act on the bonds between particles. Thus, parallel bonds that are capable of resisting moment can more accurately simulate rock and rock-like material. Therefore, to simulate rock specimens, circular particles with defined elastic moduli, friction coefficients, and radii are commonly connected by parallel bonds (Fig. 1) [15]. In the loading process, microcracks form because of bond breakages that occur when the stresses reach the shear or tensile strength of the material. Simultaneously, the numbers of the tensile and shear cracks can be dynamically recorded and output. In addition, indentation adds energy into the calculation model; the energy is then consumed by crack propagation or stored in the model.

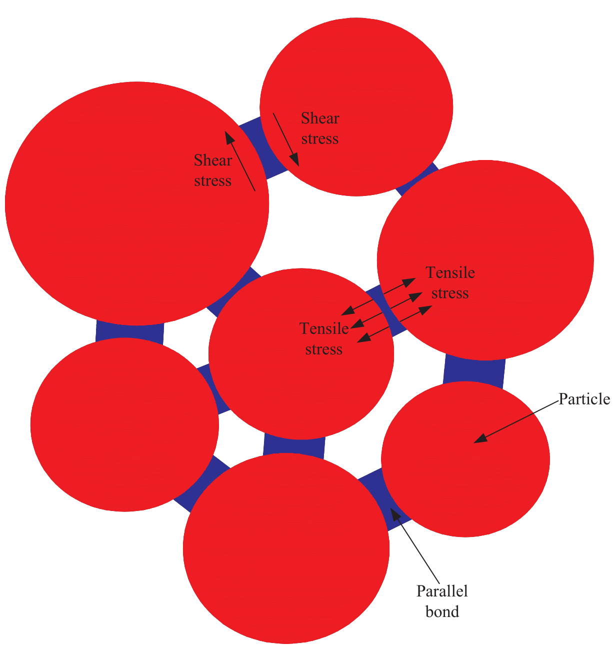

Fig. 1. Parallel bonded particles.

During the indentation process, the energy such as boundary work done by the walls and strain work stored in the bonds can be recorded. Thus, the crack propagation energy can be obtained by subtracting the stored energy from the input energy. This method of calculating the crack propagation energy was reported by Moon and Oh and Moon et al. [26,27].

In the indentation process, measurement circles with specific radii can be installed at designated locations. Within a measurement circle, the average stress tensor is as follows [28]:

$$\sigma_{ij} = \left(\frac{1-n}{\sum_{N_P} V^P} \right) \sum_{N_P} \sum_{N_C} |x_i^{(C)} - x_i^{(P)}| n_i^{(C,P)} F_j^{(C)} \tag{1}$$

where N_P and N_C are the numbers of the particles and contacts within the measurement circle, V^P is the volume of the particle; $x_i^{(P)}$ and $x_i^{(C)}$ are the locations of the particles and their contacts, $n_i^{(C,P)}$ is the unit normal vector determined by the particle center, and $F_j^{(C)}$ is the contact force. Thus, the horizontal stress, σ_h, vertical stresses, σ_v, and shear stress, τ, can be obtained within the measurement circles.

The recorded shear stress can characterize the shear crack initiation and propagation. In addition, in the PFC 2D model, the tensile and compressive stresses are positive and negative, respectively. Therefore, the maximum principle stress can characterize the tensile crack initiation and propagation. The maximum principle stress can be expressed as follows [29]:

$$\sigma_{max} = \frac{\sigma_h + \sigma_v}{2} + \sqrt{\left(\frac{\sigma_h - \sigma_v}{2}\right)^2 + \tau^2} \tag{2}$$

where σ_{max} is the maximum principle stress, σ_h and σ_v are the horizontal and vertical stresses, and τ is the shear stress.

Thus, according to the measurement circle coordinates, the recorded stresses and the calculated maximum principle stress (Eq. (2)), the stress contours can be drawn by postprocessing.

2.2. Numerical model

Before the indentation simulations, the uniaxial compressive strength and fracture toughness of the specimen were measured (Fig. 2). Fracture toughness, K_{IC}, is a critical index representing the resistance of a material to fracture propagation [26,27]:

$$K_{IC} = \sqrt{EG_{IC}} \tag{3}$$

where E is the plane strain Young's modulus and G_{IC} is the strain energy release rate, which is obtained by deriving the crack energy, U_C, in terms of crack area, A_c:

$$G_{IC} = dU_c/dA_c \tag{4}$$

where U_c is the crack energy and can be expressed as follows:

$$U_c = U_t - U_s \tag{5}$$

where U_t is the input energy and U_s is the strain energy. In PFC, the input energy and the energy stored in the form of strain energy can be recorded and output every few steps.

In PFC 2D, the fractured area is as follows:

$$A_c = N_c DL \tag{6}$$

where N_c is the number of fractured particles, D is the average diameter of the assemblage, and L is the unit depth. Accordingly, the number of fractured particles can be recorded every few steps.

By compressing a Brazilian disc with a thoroughgoing crack (Fig. 2(b)), the strain energy release rate can be obtained based on the recorded fractured area and crack energy. The micro- and macro-parameters are listed in Table 1.

To simulate the indentation process, a parallel bonded model (Fig. 3) with a width and height of 70 and 200 mm, respectively, was