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Microscopic damage field in coal induced by water jets

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ABSTRACT

This paper uses experiments and simulations to investigate the fragmentation process of coal subjected to water jets. The experiments are conducted using computed tomography (CT) and digital image processing technology to reconstruct the damage field of an impacted coal core, and a numerical model is established based on the arbitrary Lagrange–Euler (ALE) algorithm under the same impact condition. By analyzing the variations of the mechanical parameters in the simulation, this study reveals the element fragmentation mechanism. The results show that the fragmentation of an element can be divided into three stages. In addition, this research explains the formation and development of the punching based on the strain states in the simulation and verifies the deductions using experiment results. Furthermore, the paper also arrives at certain conclusions regarding variations of the damage field with coordinates. In the vertical direction, due to the resistance of reflux and the friction between jets and the punching wall, the kinetic energy of water jets is consumed gradually. Accordingly, both the distribution range and the degree of damage decrease with increasing standard depth. In the horizontal direction, the distribution of microscopic damage is characterized by locality, which occurs because of the attenuation of the acting effective stress.

1. Introduction

As currently available coal resources often require deep mining, the complexities of the geological environment pose a challenge to traditional mining techniques. Simultaneously, the need to optimize the product capacity of the coal industry also makes finding safer, more scientific, and more efficient coal mining methods a crucial task. Under such circumstances, a high-pressure water jet is favored by scholars and engineers for rock breaking because of its advantages such as high cutting efficiency, low risk, higher energy savings, environmental protection, and ease of handling. However, because rock fragmentation via water jet impact is a complex process involving a high strain rate and low transparency, even though many researchers have focused on research of the mechanism, the research contributions still lag behind the practical applications.

Studies on the mechanism of rock breaking by water jets can be divided into two major categories: experimental research and numerical research. Experimental research consists of three stages. In the first stage, experiments were performed to identify the optimal impact condition by changing the nozzle design or adjusting impact parameters such as the traverse feed rate, impact angle, jet diameter, pump pressure, and target distance. As illustration, Alberdi, A. et al. studied the effect of process parameter on the kerf geometry in abrasive water jet milling in terms of four process parameters: pressure, abrasive mass flow rate, stand-off distance, and traverse feed rate (Alberdi et al., 2010). Aydin, G. investigated the effect of particle size distribution and recycling frequency of recycling abrasive jets on the rock cutting performance (Aydin, 2015). Lu, Y et al. examined the oscillatory effect of high-pressure pulsed water jet upon the gas flow of coal-mass (Lu et al., 2010). Zhao, J. et al. performed the rock breaking experiments under various particle water jet parameters (water pressure (velocity), dwell time, particle diameter, concentration, and standoff distance) (Zhao et al., 2017). Sharma, D. V. estimated the effect of nozzle designs on gas induction in jet loop reactors (Sharma et al., 2017). Besides, some contributions to research on the effect of environment temperature, abrasive filling, oscillation frequency, and cavitation on the cutting performance of the water jet were also proposed. For instance, Sitek, L. et al. investigated the effects of flat high-speed water jet on concretes affected by high temperature (Sitek et al., 2013). Aydin, G. et al. used solid-cutting waste of granite as an alternative abrasive for abrasive water jet cutting of marble (Aydin et al., 2017). Foldyna, J. used ultrasound to enhance the performance of high-speed water jets (Foldyna, 2004). Studies in this stage were mainly focused on the practical applications. In the second stage, researchers tried to find the reason for

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(*a*) Water jet machine (*b*) CT scans equipment

Fig. 1. Experimental devices.

rock fragmentation by analyzing the pattern of erosion pits and the microstructure of the cutting surface (Dehkhoda and Hood, 2013; Liu et al., 2015a). Surface detection methods, such as scanning electron microscopy (SEM) (He et al., 2016) and illumination photography (Momber, 2006), were adopted in this stage. Some theories were proposed, but the studies were still confined to the rock surface. The third stage was based on internal structure detection. Technologies such as ultrasonic technology (Liu et al., 2015a), acoustic emission (AE) (Dehkhoda and Hood, 2014), and computed tomography (CT) (Xue et al., 2017, 2018) were adopted to detect the internal structure of rock. The microscopic damage induced inside the rock was the primary focus in this stage.

The development of numerical research is similar to that of experiments. First, some simple numerical models were established to determine the process of rock fragmentation under the impact of water jets, and different jet parameters were designed in the model to compare the calculation results with experimental data. In this stage, the researchers' attention was focused on the fragmentation performance of rock or some traditional stress parameters, such as the principal stress and shear stress. For example, Junkar M et al. and Kumar N et al. presented the application of an elasto-plastic model based explicit finite element analysis (FEA) to model the erosion behaviour in abrasive water jet machining (Junkar et al., 2006; Kumar and Shukla, 2012). Wang R et al. developed a two-fluid model based on the fundamental laws of conservation to model the abrasive water jet (Wang and Wang, 2010). Gong W et al. modeled the abrasive jet by defining the respective percentage of abrasive and water volume fraction in an Euler grid based on the function of *INITIAL_VOLUME_FRACTION in LS-DYNA (Wenjun et al., 2011). With the development of the numerical method, some high-quality material models, such as J-H-C (Johnson-Holmquist-Concrete) (Liu et al., 2015b; Holmquist and Johnson, 2008) and JH-II (Johnson-Holmquist II) (Jiang et al., 2017), were adopted to characterize the mechanical behavior of rock. Thus, the mechanical response of rock was refined. Certain complex parameters, such as the effective stress and effective plastic strain, were included in the analysis, and the effect of stress waves (Xue et al., 2017) on rock fragmentation was emphasized. In the third stage, researchers focused not only on the stress state of rock but also on the damage field and fissure field. They combined the variations of different parameters to reveal the mechanism of rock fragmentation, which is also the current mainstream approach (Jiang et al., 2017; Wang et al., 2017).

Existing studies indicate that the research focus of rock fragmentation under water jets has moved from the rock surface to the internal structure and has changed from univariate analysis to multivariate comprehensive analysis. Therefore, this paper investigates the fragmentation process of coal based on a comprehensive analysis using experiments and simulations. The numerical model is established based on the ALE-FEM algorithm, and the experiment is performed by relying on CT scans and digital image processing technology. In contrast to the previous contributions, this paper reconstructs the internal structure of an impacted coal core, and the distribution of the microscopic damage field is visualized. Based on the variations of different mechanical parameters of the model, this research reveals the coal fragmentation mechanism and verifies the deductions with experiments. Moreover, the distribution characteristics of the damage field are determined and explained by the evolvement of the stress state.

2. Experiments

2.1. Sample and devices

The coal samples used in the experiment were acquired from the N2311 coal face in the Songzao coal mine. The main coal variety of the coal mine is anthracite, which has a high carbon content, low volatilization, high density, high hardness, a high ignition point and no smoke at the time of combustion.

The jet machine (LTJ2040-5A) adopted in this experiment is a five-axis intelligent water jet machine manufactured by Shanghai SHIMAI corporation (Fig. 1 (*a*)). The diameter of the nozzle is 0.889 mm. Due to the divergence phenomenon of the water jet, the diameter of the jet at the outlet is approximately 1 mm. The pump pressure adopted in the experiment is 70 MPa.

The CT system applied to scan the impacted coal samples is a High-Resolution Industry CT Real-time Imaging System (Fig. 1 (*b*), ACTIS300-320/225CT/DR), which was codesigned by the State Key Laboratory of Coal Resources and Safety Mining of China University of Mining & Technology (Beijing) and American Bio-Imaging Research (BIR) Inc. (Peng et al., 2011). The resolution in the slice plane and the resolution along the slice height are each approximately 85 μm.

2.2. Experimental procedures

(1) *Sample preparation.* To reduce the interference of the natural pores and fractures, the rock blocks selected for coring are relatively complete and have less initial damage. After coring, the samples are polished so that the ends are parallel to one another and vertical to the central axes of the samples. This ensures that a series of slices can be obtained as stable concentric disks when the samples are placed on a turntable. The coal sample used in the experiment is a cylinder with a diameter of 50 mm and a height of 70 mm.
(2) *Jet impact and CT scans.* The coal samples are prepared for impact with a high-pressure water jet. After jet impact, the sample is used to carry out CT scan tests, and a 16-bit gray image with 660 × 660 voxels based on 1440 views is obtained.

2.3. Image processing

Through data processing, 820 8-bit grayscale images are extracted. To filter the damage field induced by the water jets, in this study, the images are segmented according to their gray histograms. Fig. 2 shows some typical CT slices and the corresponding gray histograms. Fig. 2 (1) and Fig. 2 (2) show the slices at heights of 69.7 mm and 57.25 mm,