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Digital-image Based Numerical Simulation on Failure Process of High-sulfur Coal

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Abstract

Crushing of high-sulfur coal was important for physical desulfurization, but there were little research on crushing mechanism. This paper combined digital image processing technology and rock failure process analysis system RFPA^{2D} to simulate the failure process of high-sulfur coal in Pu'an of Guizhou under uniaxial compression, and discussed the influence of horizontal restraint, existence and different geometric distribution of pyrite particle on mechanical performance and failure process of high-sulfur coal. The numerical results indicated that without horizontal restraint the compressive strength of high-sulfur coal was lower and monomial dissociation of pyrite particle was more sufficient than that with horizontal restraint. The compressive strength of coal containing pyrite particle was larger than that of pure coal and there was stress concentration in upper and lower pyrite particle during failure process. When pyrite particle distributed in the middle position of a coal sample, the compressive strength was higher than that of the other three positions, but monomial dissociation of pyrite particle was more sufficient than that of the other three positions, and this was beneficial to the following desulfurization operation. The study had certain reference value for crushing mechanism, crushing process design, selection of breaking equipment and energy saving and consumption reduction.

Key words: *digital image, high-sulfur coal, pyrite, numerical simulation*

1. Introduction

China is a country with large coal reserve, yield and consumption. The use of high-sulfur coal directly influences the environment as well as the development of coal industry in our country. As coal is China's primary energy, coal desulfurization is of large realistic significance [1]. In our country high-sulfur in coal can be mainly attributed to the pyrite, and thus the desulfurization technology before coal combustion is extensively used. Since the process and operation of physical desulfurization are relative simple, the cost is low and it can remove 50% to 80% of pyrite, it is now widely used in the desulfurization of industrial. Crushing operation is required before physical desulfurization and occupies an important position in coal preparation plant. Suitable crushing firstly could make raw coal meet the particle size requirements of cleaning unit, secondly reach dissociation of coal, gangue and pyrite and avoid overgrinding, thirdly meet the requirements of the consumers for coal granularity. Besides, the production cost and investment of crushing operation account for most of the total of a coal processing plant. Crushing operation has a direct influence on the economic index of coal preparation plant [2]. So it will be of great importance in designing crushing process, selecting crushing equipment and save energy and reduce consumption to study the crushing mechanism of high-sulfur coal.

Coal broken researches mainly focus on three aspects as breaking of top-coal, recleaning after middling coal crushing and preventing overgrinding of lump coal. Zhao et al. [3] analyzed the extension of crack and the breaking mechanism of top coal caving in steep seam by applying fracture mechanics theory. Zhang et al. [4] studied the mechanics characteristic of combination system for coal and rock parting, investigated the failure mechanism of top-coal with rock parting, advanced key technical measures of improving the caving behavior of top-coal

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with rock parting. Liu et al. [5] gave a crushing criterion under an impact load, and provided theory basis for the impact broken of lump coal. The experiment results of Yang et al. [6] showed that the cleaned coal could be fully recovered from the re-preparation of the middlings after crushed and would bring good economic and social benefits to the enterprise. Tao et al. [7] analyzed the reasons of overgrinding of lump coal in crushing process, thus put forward the crusher reconstruction project and introduced the effect after transformation. However, there were little research on crushing mechanism of high-sulfur coal. Numerical experiment is an appropriate method for crushing mechanism study, because in actual situation there are many influencing factors and the particle failure process is complex [8]. Jun Li et al.[9] researched the coal pulverized catches fire and steadily combustion mechanism through the numerical simulation of the 300MW tangentially pulverized coal fired boiler. In recent years, digital-image processing technology has a rapid development. Hartati, Sri et al. [10] discussed the development of a high-resolution digital microscope and the image processing utility. It becomes a convenient and effective method for research on mechanical behavior of rock or ore failure process when the digital-image processing technology has been applied in rock failure process analysis system [11]. This method could more accurately reflect the complexity of the fine structure of the rock material.

Sulfur in high-sulfur coal from Pu'an of Guizhou mainly exists in the form of pyrite. In order to use physical process to decrease the sulfur grade, crushing operation is firstly used to make coal and pyrite dissociated. In order to understand the failure mechanics characteristics of high-sulfur coal under uniaxial compression and analyze the crushing mechanism of high-sulfur coal, digital image processing technology and RFPA^{2D} system were combined together for the study in this paper. Digital image processing technology was applied to characterize the spatial distribution of pyrite in the high-sulfur coal sample, statistical methods were used to describe the heterogeneity of pyrite and coal. As a result, we established a numerical damage model simulating the failure process of high-sulfur coal samples under uniaxial compression. And the influence of horizontal restraint, existence and different geometric distribution of pyrite particle on mechanical performance and crushing process of high-sulfur coal were all analyzed in detail.

2. Research Method

RFPA^{2D} is a rock failure process analysis system with elastic mechanics for stress analysis tools, elastic damage theory and its revised coulomb failure criteria for medium deformation and failure analysis module [12]. Its functions include two aspects such as stress analysis and damage analysis [13]. Stress analysis of RFPA^{2D} is to use the finite element method, while destroy analysis is to check whether there is a material failure element according to failure criteria, and then to process the failure element by rigidity degradation (treatment separation) and stiffness reconstruction (processing contact) method. The RFPA^{2D} simulates the loading condition of test enginery by the displacement loading method. For the given displacement incremental of every step first do stress calculation, then check whether there is failure element in model according to failure criteria. If there is no failure element, it would continue to add a displacement increment and do the stress calculation of the next step. If there is failure element, it would process stiffness degradation according to pull or cut destruction state of element and then restart to do stress calculation of the current step. Repeat the process until the whole material produces macroscopic damage. Due to the brittleness destruction of the element, elastic energy released by destruction of the element is regarded as the form of acoustic emission [13, 14]. It could observe rock failure process according to acoustic emission characteristics.

RFPA^{2D}-DIP (Realistic Failure Process Analysis based Digital Image Processing) introduces digital image processing technology to characterize the microstructure of rock, concrete and other heterogeneous materials. The papers [15-17] all apply digital image processing technology to characterize the distribution of minerals in the rock. After inputting the digital images of research samples, digital image processing technology is used to analyze the color feature of the images, identify the various types of micro-media, offer appropriate material numbers to them, and determine their material areas. The software automatically processes the heterogeneity representative images into finite element mesh and thereby establishes numerical models that can reflect the microstructure of the materials. Taking advantage of the software's fast and convenient material assignment function, we can assign the meso-media, enter their constitutive equation control parameters, and then set the boundary conditions and analyze the mechanical behavior and failure process under external loads. The details of digital-image based RFPA^{2D}-DIP please refer to literature15-17.

Select a high-sulfur coal representative sample in Pu'an of Guizhou, and the surface image of the high-sulfur coal obtained by digital camera is shown in Figure 1. The size of the image is 100×200 pixels, and the actual size is 25mm×50mm. The lighter one is pyrite, while the darker one is coal. The image changed into bitmap file of BMP format is imported into RFPA^{2D} software. Because the high-sulfur coal image is gray image, different images are segmented by the difference of the color strength in color space of HIS. The change of value I on scan line AB is shown in Figure 2. Comparing line AB through the coal and pyrite in Figure 1 and the change of curve in Figure 2, it can be seen that the brightness of coal (I value) is below 80, and the brightness of pyrite is above 80. After repeated trials, we finally decide to take I = 80 as the segmentation threshold for image. Figure 3 shows the result after segmentation: the darker one is coal, and the lighter one is pyrite. It can be seen from the figure that the shapes and spatial distribution of pyrite are more accurate after the image is processed by the digital image processing technology.

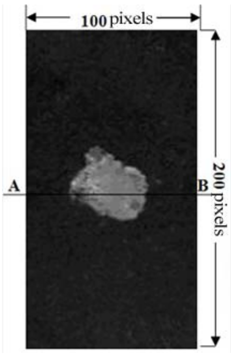


Figure 1. Surface image of the high-sulfur coal

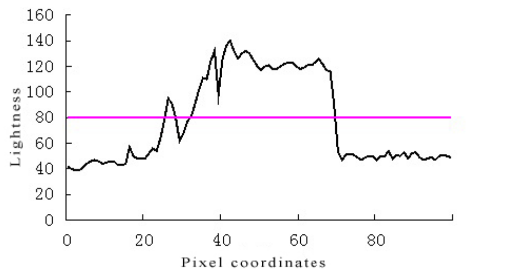


Figure 2. Value I curve on scan line AB

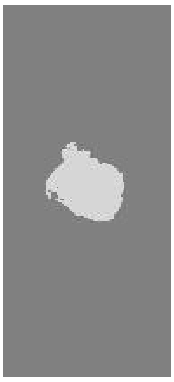


Figure 3. Image after segmentation threshold

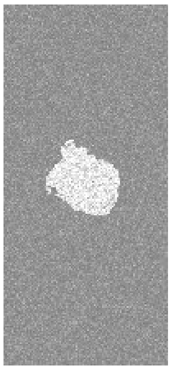


Figure 4. Numerical model established after digital image processing

The numerical model established after digital image processing is shown in Figure 4. The lighter it is, the higher the elastic modulus is. The basic mechanical parameters of coal and pyrite are in Table 1. The actual size of the model is 25mm×50mm, which is divided into a 100×200 grid with the size of each unit being 0.25mm×0.25mm. According to the standard of Wittmann [18] for classifying the macro, meso and micro scale (macro>10-1m, meso=0.5×10-3~10-1m, micro <0.5×10-3m), it can be considered that the scale of pyrite is in the mesoscopic range, and the scale of coal is in the microcosmic range. After establishing meso-micro relation through Weibull distribution. In order to investigate the influence of horizontal restraint, existence and different geometric distribution of pyrite particle on mechanical performance and crushing process of high-sulfur coal, six numerical models established by RFPA2D system are shown in Figure 5.

Table1. Mechanical parameters of the samples of high-sulfur coal and pyrite

Sample	The average value of elasticity modulus/GPa		The average value of uniaxial compressive strength/MPa		Poisson ratio μ	The ratio of compressive strength to tensile strength	Volume weight/ kg·cm-3	Angle of internal friction ψ/(°)	Homogeneity
	macroscopy	mesoscopy	macroscopy	mesoscopy					
High-sulfur coal	3.6	4.5	43	139	0.33	37	2.80	22	2
Pyrite	18.2	20.8	64	144	0.14	10	3.83	32	5

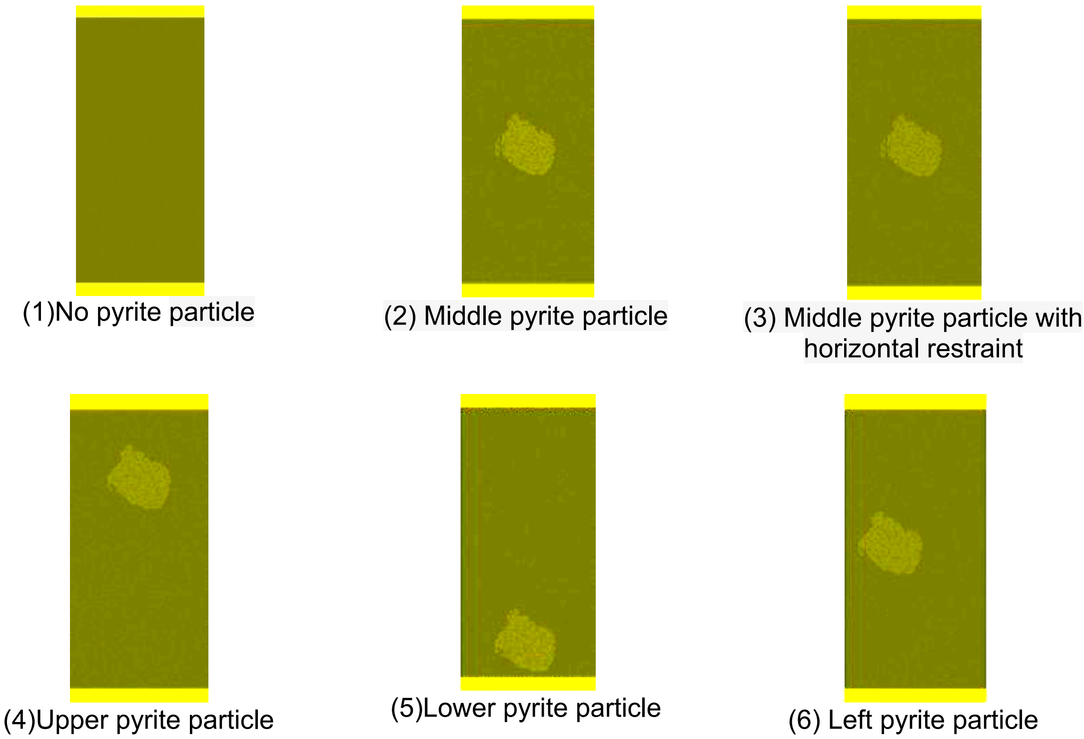


Figure 5. High-sulfur coal particle model (obtained from RFPA^{2D} modelling)

3. Results and Discussion

The transformation process from injury to failure for high-sulfur coal under uniaxial compression was numerically simulated by conducting the above numerical models. In order to simulate contact characteristics of high-sulfur coal sample and press machine, loading steel plates are set at both ends of the sample, which are of 10 mm thick, homogeneous and elastic, and the Young's modulus of which is 300GPa, the compressive strength is 1000MPa, the poisson's ratio is 0.18. Being regarded as a plane stress problem, the failure process is conducted by progressive loading controlled by stepwise displacement, until the high-sulfur coal sample appears macroscopic damage. Loading step of 0.01 mm / step and total loading step of 450 steps are set in this numerical simulation.

3.1 Effect of Horizontal Restraint on the Failure Process of High-Sulfur Coal

The load-displacement curves of high-sulfur coal with and without horizontal restraint are shown in Figure 6, while Figure 7 shows the distribution and comparison of the maximum principal stress fields, the gray level of which reflects the relative size of element stress. The lighter it is, the higher the stress is.

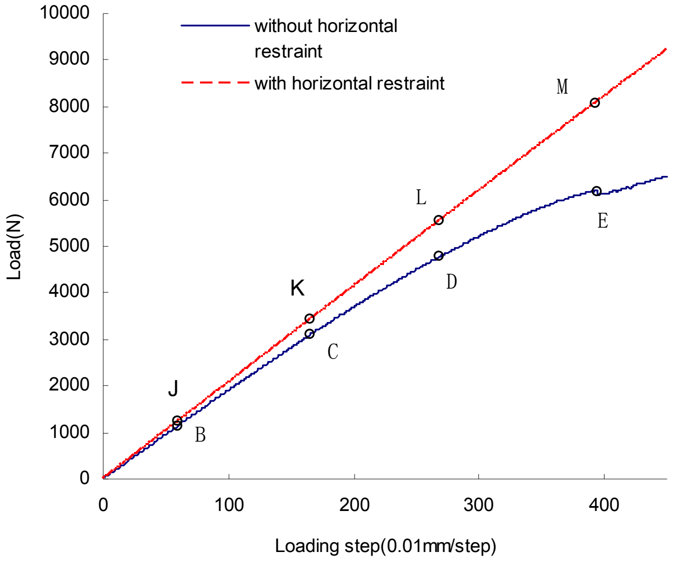


Figure 6. The load-displacement curves for high-sulfur coal with and without horizontal restraint

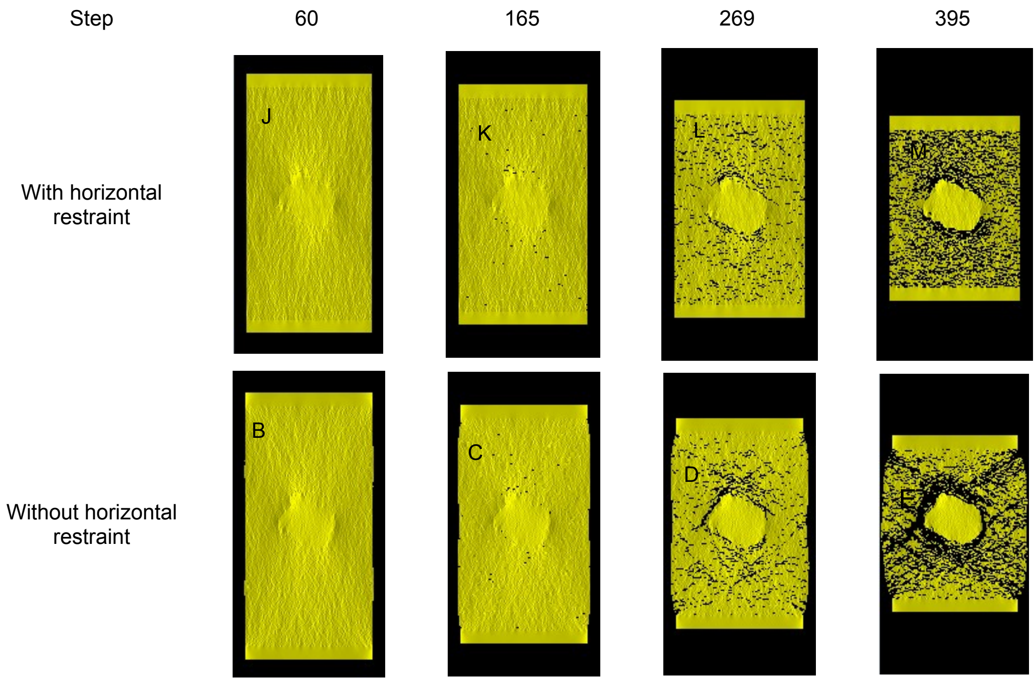


Figure 7. maximum principal stress fields with and without horizontal restraint

Figure 6 shows that without horizontal restraint when the load-displacement curve reaches certain load (E point), the curve has a brief downward trend around Step 395 and then continue to rise, showing a distinct nonlinear deformation stage (CE section). This can be attributed to that the local micro failures in the sample increase gradually and gather together. However, with horizontal restraint, the load-displacement curve with horizontal restraint rises gradually (JM section), whose nonlinear deformation stage is not obvious. Besides, the curve without horizontal restraint is below that with horizontal restraint, which indicates that in the same loading step, the compressive strength of high-sulfur coal sample without horizontal restraint is smaller than that with horizontal restraint.

The labels of B, C, D, E, J, K, L, M in Figure 7 are corresponded with the loading levels marked in Figure 6 respectively. Figure 7 shows that stresses in the two cases (with and without horizontal restraint) are both mainly concentrated in the upper and lower part of the pyrite particle, namely the polar region. However, with horizontal restraint, micro failures in the polar region of the pyrite particle expand at a lower speed only along the interface but not lateral and also do not form diagonal macroscopic cracks. In this case, the monomial dissociation of pyrite particle is not as sufficient as that without horizontal restraint.

3.2. Comparison of Mechanical Analysis of Failure Process of High-Sulfur Coal Sample and Pure Coal Sample

Analysis is made by conducting a numerical simulation experiment for the failure process of both high sulfur coal sample and pure coal sample without horizontal restraint, and then the two cases are compared. The load-displacement curves are shown in Figure 8 while the maximum principal stress fields are shown in Figure 9.

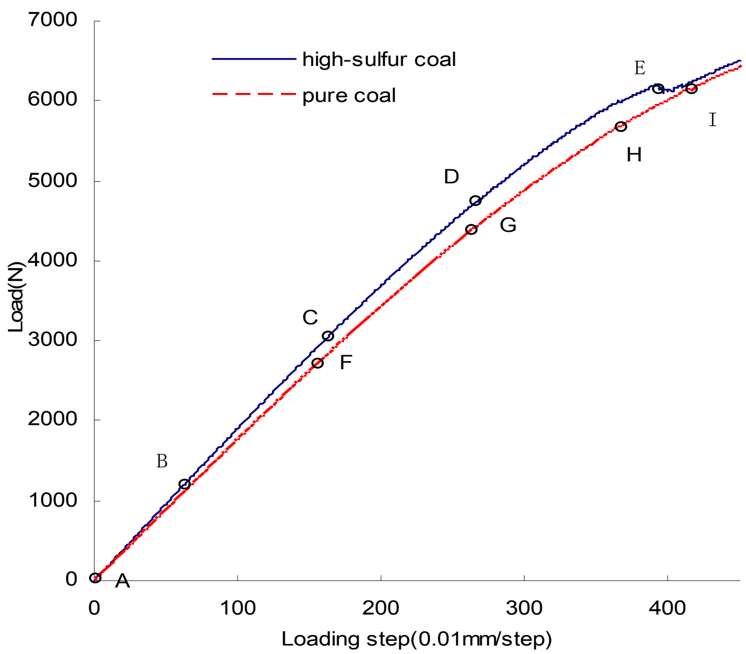


Figure 8. The load-displacement curves for high sulfur coal sample and pure coal sample

Figure 8 shows that the load-displacement curves of two samples respectively reach certain load and then have a brief downward trend, and then continue to rise. However, during the nonlinear deformation stage, the load-displacement curve of the high-sulfur coal shows a more distinct non-linearity than that of the pure coal, which indicates that the existence of pyrite particle has great influence on the mechanical properties of the coal sample. Besides, high-sulfur coal's load-displacement curve is above the pure coal's curve, showing that in the same loading step, the compressive strength of high-sulfur coal is larger than that of pure coal. High-sulfur coal sample forms macro damage at E point with a vertical load of 6157.01N, while pure coal sample forms macro damage at I point with a vertical load of 6141.52N, which indicates that the existence of the pyrite particle improves the compressive strength of coal sample.

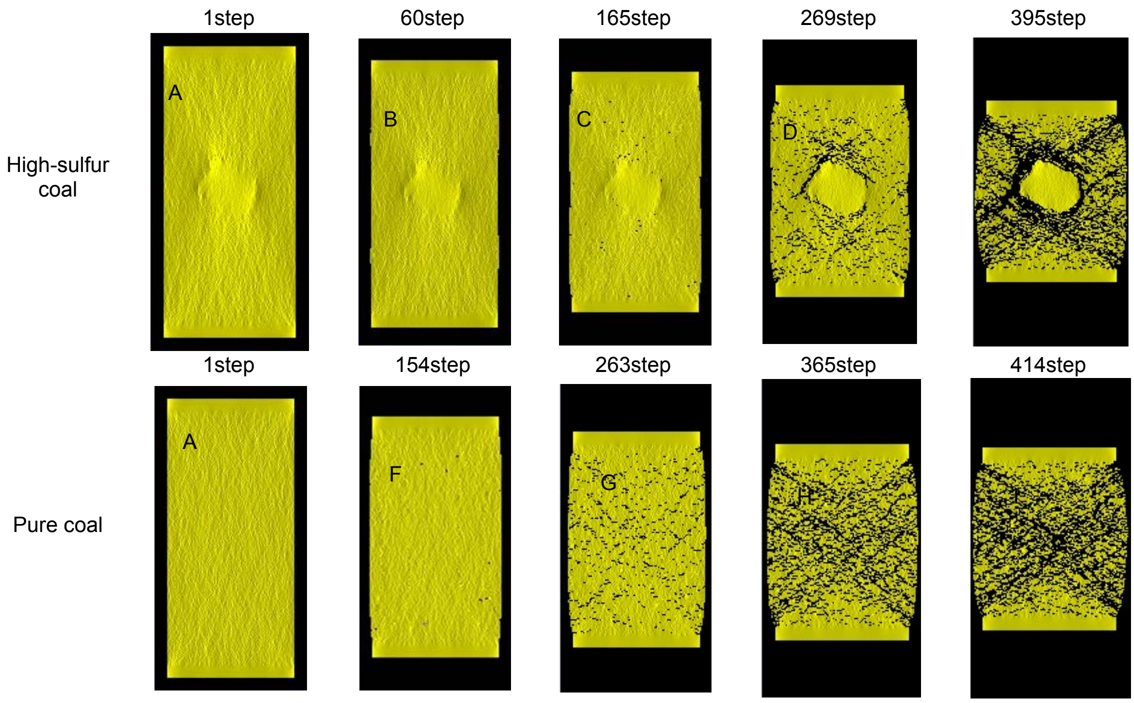


Figure 9. maximum principal stress fields for high-sulfur coal and pure coal

The labels of A, B, C, D, E, F, G, H, I in Figure 9 are corresponded with the loading levels marked in Figure 8 respectively. Figure 8 shows that the stresses in the pure coal distribute relative uniformly, and with the increase of external loading, various elements of the pure coal sample begin to injury randomly, damage and form local micro cracks, eventually form macroscopic cracks and cause lateral expansion. However, there is an obvious stress concentration in high-sulfur coal. The stress is mainly concentrated on the upper and lower part of the pyrite particle. Therefore, elements of these two polar areas begin to injury, damage and form micro cracks, and with the increase of external loading, the micro cracks expand along the interface into coal, eventually form macroscopic cracks along the diagonal and interface and cause lateral expansion of sample.

3.3. Effect of Different Geometric Distribution of Pyrite Particle on Failure Process of High-Sulfur Coal

Numerical simulation experiments are conducted on failure processes for different high-sulfur coal samples containing pyrite particles which are located in four different positions inside the sample, namely the upper, middle, left, and lower positions, without horizontal restraint. The load-displacement curves and maximum principal stress fields for those four cases are shown in Figure 10 and Figure 11.

The labels of O, E, P, N in Figure 10 represent the vertical load values respectively when the four high-sulfur coal samples with pyrite in four different positions appear its macro damage. Figure 10 shows that the load-displacement curves of four samples have the similar trend in linear elastic stage (AQ section), which indicates that different geometric distribution of pyrite particle has little effect on linear elastic stage of high-sulfur coal. However, the nonlinear deformation stage of four curves are quite different, which indicates that different geometric distribution of pyrite particle have a certain effect on the mechanical properties of high- sulfur coal sample. Comparison of the vertical load values of the label O, E, P, N reveals that when pyrite particle is located in the middle of high-sulfur coal sample, the compressive strength of the sample is larger than the three other positions.

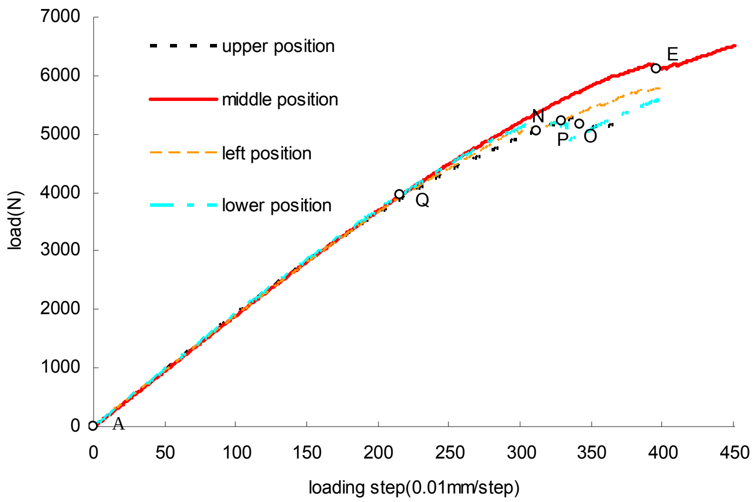
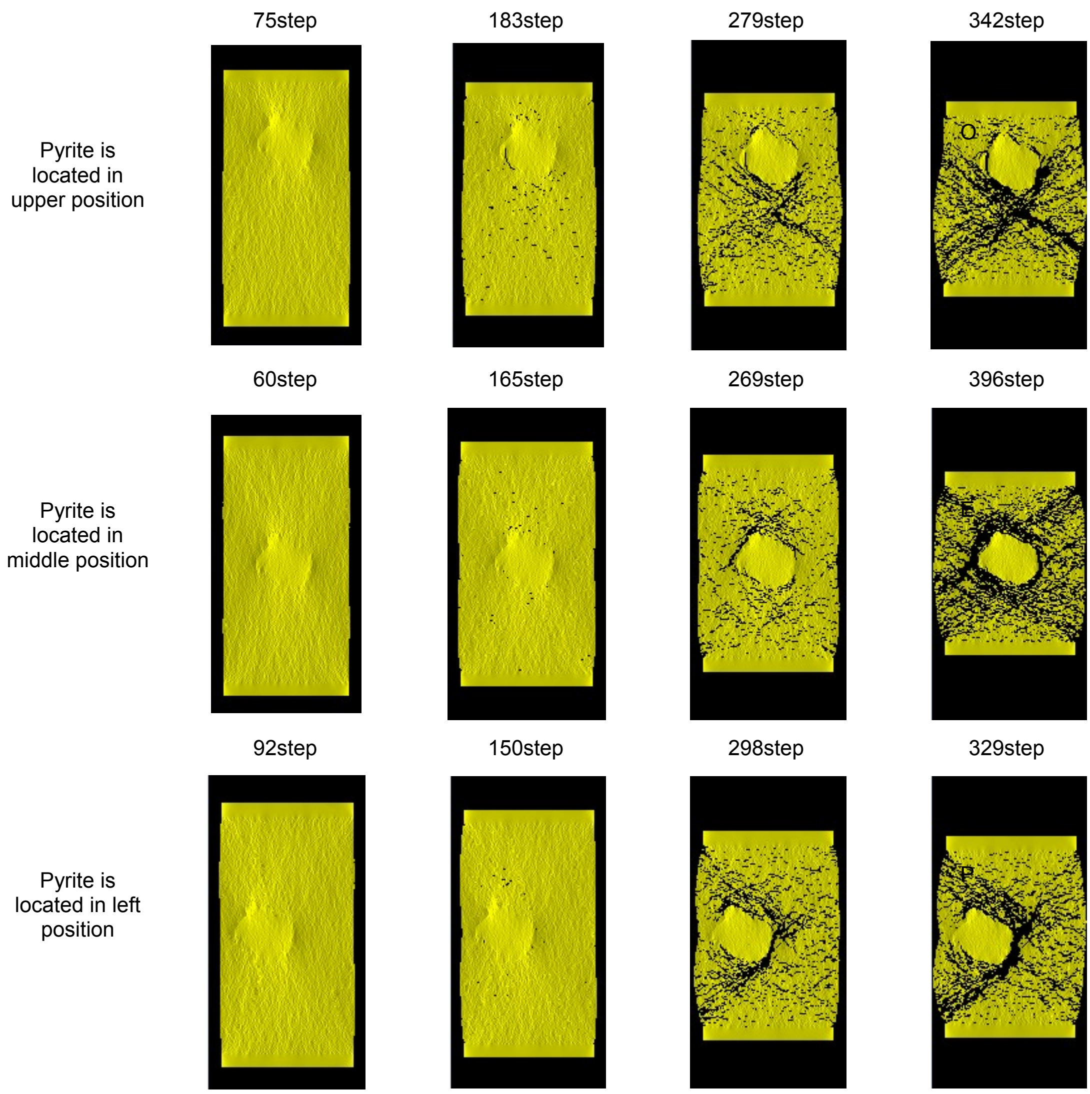


Figure 10. The load-displacement curves for coal sample containing pyrite particle that located in the upper, middle, left, lower position



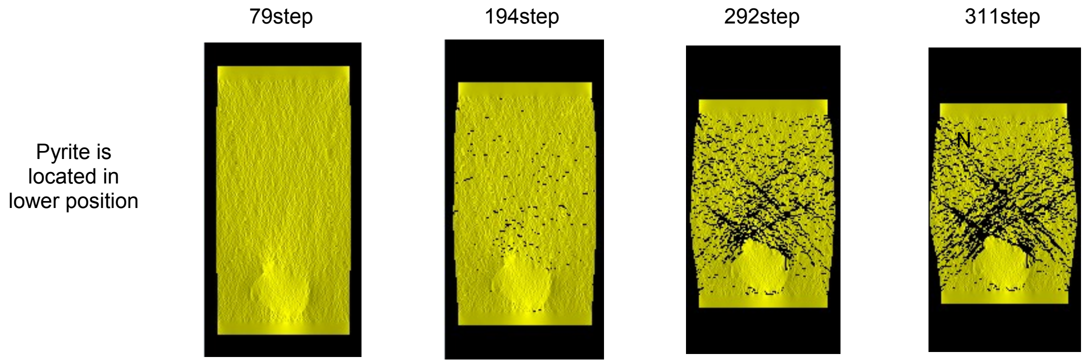


Figure 11. maximum principal stress fields for coal samples containing pyrite particle which is located in the upper, middle, left, lower position

The labels of O, E, P, N in Figure 11 are corresponded with the loading levels marked in Figure 10 respectively. The stress in four cases are all mainly concentrated in upper and lower part of the pyrite particle, and micro cracks begin to emerge in the upper and lower part of the pyrite particle and interface, and gradually expand along the interface and diagonal, eventually lead to the macro damage of the sample. When pyrite particle is located in the middle of a high-sulfur coal sample, monomial dissociation of pyrite particle is more sufficient than that of the three other positions, this is beneficial to the following desulfurization operation.

4. Conclusion

Horizontal restraint has a certain effect on compressive strength of high-sulfur coal and degree of dissociation of pyrite particle. Under uniaxial compression, without horizontal restraint the compressive strength of high-sulfur coal is lower and the monomial dissociation of pyrite particle is more sufficient than that with horizontal restraint. So in order to improve the breaking efficiency and reduce the energy consumption, horizontal restraint force for high-sulfur coal in crushing cavity should be reduced. The existence of pyrite particle has great influence on the mechanical properties and stress distribution of coal sample. Compared with pure coal, the compressive strength of coal containing pyrite particle is larger and there is stress concentration in upper and lower part of the pyrite particle during crushing process. So in actual crushing process of high-sulfur coal, pure coal is broken more easily than high-sulfur coal, while high-sulfur coal pyrite is easy to be dissociated. Different geometric distribution of pyrite particle in coal sample has little effect on the mechanics properties of high-sulfur coal in linear elastic stage but has a certain effect in nonlinear deformation stage. When a pyrite particle is located in the middle of a high-sulfur coal sample, the compressive strength of which is larger than the three other samples with pyrite particles in other positions, and also the monomial dissociation of the pyrite particle is more sufficient than that of three other cases, this is beneficial to the following desulfurization operation. However, in actual crushing process, the position of pyrite particle is random, so after crushing there will be intergrowth with pyrite produced. During coal processing, this intergrowth with pyrite generally goes with the middlings. In order to recycle the resources, middlings may need to be crushed and beneficiated again.

Acknowledgments:

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