Mechanical response and energy dissipation characteristics of granite under low velocity cyclic impact

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Abstract. In the process of metal ore blasting mining, the surrounding rock in the middle and far area will still be affected by the stress wave generated by the explosion, resulting in the damage and strength reduction of surrounding rock. The fracture process of rock under cyclic impact load is a process of energy absorption and dissipation. The research on the mechanical properties and energy dissipation law of surrounding rock under low velocity cyclic impact has a good reference for the research on the damage law of rock under weak impact environment. In this paper, the granite samples collected from Sanshandao Gold Mine in Laizhou City, Shandong Province were subjected to cyclic impact tests by using a 50 mm diameter split Hopkinson pressure bar (SHPB) test device. The stress-strain evolution law and energy dissipation law of the specimen in the process of damage and fracture are mainly studied. The results show that the dynamic process of a large number of void defects (such as voids, dislocations, microcracks, etc.) in granite under cyclic impact load is strengthened, and the damaged core is formed and propagated, leading to tensile fracture; With the accumulation of strain energy, the damage situation intensifies, and then affects the stress propagation, so that the ratio of incident energy to reflected energy increases linearly with the accumulation of strain energy, and the ratio of transmitted energy also decreases linearly.

Key words: cyclic impact SHPB energy damage.

1. Introduction
In the process of metal mine blasting mining, there will be different strength of cyclic impact load [1-2]. The surrounding rock with different distances around the blasting point will appear different degrees of damage cracks under multiple impact loads [3]. Especially for the surrounding rock in the far away area, the damage is often weak, so it is easy to be ignored. However, under the cyclic impact load, the damage will gradually accumulate and form a potential safety hazard. Therefore, it is of great significance for mining safety to study the damage and failure law of rock mass under low-speed cyclic impact.

In recent years, scholars at home and abroad have carried out a lot of research work on the mechanical properties of rock materials under impact. Luo et al. [4] revealed the dynamic impact fatigue characteristics of this kind of rock by analyzing the mechanical properties and fatigue damage evolution of iron ore under cyclic impact load; Zhu Jingjing et al. [5] used SHPB The device carries out cyclic
impact compression test on granite specimens, studies the stress and strain characteristics of rock under multiple impacts, and analyzes the cumulative damage evolution law of rock; Li Liyun et al. [6] conducted failure test on sandstone under impact load with different strength, and found that there is a functional relationship between the damage variable of rock and impact velocity; Lu Xiaohong et al. [7] studied sandstone with SHPB equipment. The dynamic mechanical properties of sandstone under different confining pressure levels and different strain rates are studied. The relationship between energy accumulation absorption value, damage degree and confining pressure is analyzed. Ping Qi et al. [8] carried out the cyclic impact test on limestone, and found that limestone has obvious size effect under impact load. The dynamic compressive strength and dynamic elastic modulus first increase and then decrease with the increase of sample length, and the peak value appears when the sample length is 60 mm. Gong Fengqiang et al. [9] conducted SHPB tests on sandstone under different confining pressures, and studied the quantitative relationship between strain rate and compressive strength of sandstone in the process of tension and compression. The expressions of dynamic Hoek Brown criterion and dynamic Mohr Coulomb criterion in different strain rate ranges are obtained. Huang et al. [10] obtained the relationship between the crack propagation law and the accumulation of impact energy through SHPB cyclic impact test and CT scanning of granite specimens. Ren Xingtao et al. [11] studied the dynamic mechanical parameters under different strain rate loading, and found that the mechanical properties of granite under dynamic compression and dynamic splitting show significant strain rate effect. The validity of the experiment is verified by numerical simulation. Wang et al. [12] pretreated granite specimens with high temperature, and combined with SHPB test, measured the dynamic stress-strain curve of the specimens, and obtained the rule of damage threshold under different temperatures; Xu Jinyu et al. [13] studied the dynamic mechanical properties and energy dissipation rule of different kinds of rocks under different confining pressures and different impact load cycles by using SHPB equipment with confining pressure. The relationship between rock damage degree and cumulative energy absorption value under confining pressure is obtained.

To sum up, the existing work focuses on the mechanical law of rock failure under impact load, or the influence of different external environment on rock fracture, while the energy dissipation law of rock specimen under cyclic load is lack of further research.

In engineering practice, the damage process of rock under cyclic impact load is closely related to the energy dissipation. Therefore, it is of great significance to study the energy dissipation law of rock in the process of cyclic impact to optimize the efficiency of metal mining and improve the production safety.

In this paper, split Hopkinson pressure is used Bar (SHPB) is used to carry out the equal strength cyclic low velocity impact test on granite specimens, and the mechanical evolution law of granite in the impact process is analyzed. Then the process of energy transmission and dissipation is studied. Combined with the principle of damage mechanics, the energy dissipation characteristics in the process of original crack formation, crack propagation and penetration are analyzed, which is helpful to the surrounding rock in the process of mining. The stability analysis can be used for reference.

2. Theoretical basis and experiment of SHPB

2.1. Test equipment and samples
The granite samples studied in this experiment come from the Sanshandao Gold Mine in Laizhou City, Shandong Province at - 960 m level. After coring, cutting, grinding and other processes, and according to the recommendations of the international society of rock mechanics on the length diameter ratio of rock samples under impact load [14], a specimen with a diameter of 50 mm and a thickness of 25 mm was made. During the test, both ends of the specimen were smeared with grease to improve the coupling between the specimen and the impact bar.

Alt1000 SHPB device and its data acquisition and processing system are used in the experiment, as shown in Figure 1. When the impact rod (bullet) in the gun chamber impacts the elastic input rod at a certain speed, an incident pulse I (stress wave) is generated in the input rod. The stress wave reaches the
specimen through the elastic input rod, and the specimen deforms at a high speed under the action of the stress pulse. While the stress wave passes through the shorter specimen, the reflected pulse enters the elastic input rod and the transmitted pulse enters the output rod. The impact velocity of the bullet can be obtained by using the velocimeter, and the strain pulse recorded by the strain gauge attached to the elastic rod can be used to calculate the dynamic stress and strain parameters of the material.

Figure 1. ALT1000 SHPB device and its data acquisition and processing system

2.2. SHPB test principle

The Hopkinson rod technique is based on the first-order elastic stress wave theory and uniform assumption, in which the energy carried by the stress wave $\sigma(t)$ is obtained by equation (1):

$$W = \frac{A_i E_i}{c_e} \int_0^t \sigma^2(t) dt$$

(1)

Among them, $A_i$ is the cross-sectional area of the input and output rods; $E_i$ is the elastic modulus of the input and output rod materials; $c_e$ is the one-dimensional stress wave velocity. And in the elastic phase, the speed of the stress wave $c_e$ can be expressed by the mass density $\rho_e$ and elastic modulus $E_e$ of the pressure rod, there are

$$c_e = \frac{E_e}{\rho_e}$$

(2)

Therefore, the energy formula of stress wave is simplified as follows:

$$W = \frac{A_i E_i}{c_e \rho_e} \int_0^t \sigma^2(t) dt$$

(3)

According to the above formula, the total dissipated energy of rock $W_d$ in SHPB dynamic impact can be expressed as:

$$W_d = W_i - (W_r + W_t)$$

(4)

Where, $W_i$, $W_r$, and $W_t$ are incident energy, reflection energy and transmission energy respectively.

3. Test results and analysis

3.1. Analysis of failure morphology and mesomechanism of granite specimens

During the test process, the single impact failure test is carried out on the specimen, and the ultimate acceleration pressure of the specimen is determined to be about 0.18 mpa. In the later stage, 50% of the
ultimate acceleration pressure was used for low-speed cyclic impact test. Under the condition of low-speed cyclic impact failure, the whole granite specimen presents axial splitting crack. And the number of fragments is small, and the fragmentation is large, as shown in Figure 2.

![Fig. 2 failure mode of specimens under low velocity cyclic impact](image)

From the point of view of damage mechanics, under the impact load, the original microcracks in the specimen are activated, forming a stress release area, resulting in cumulative damage, resulting in the deterioration of material strength and stiffness, and eventually failure. Based on the statistical mesoscopic theory, a dimensionless damage variable, crack density $C_d$ is defined:

$$C_d = \beta_c \int_0^\infty n(c,t)c^3 dc$$

(5)

$C_d$ characterizes the degradation of the macro-mechanical properties of rock materials caused by micro-crack damage, where $\beta_c$ is the crack geometric factor. The density of microcracks is a function of time, and $\frac{\partial C_d}{\partial t} > 0$, we can get:

$$\frac{\partial C_d}{\partial t} = \frac{\partial}{\partial t} \int_0^\infty n(c,t)\beta_c c^3 dc = \beta_c \int_0^\infty \left[n c^3 + n \left(3c^2 \dot{c}\right)\right] dc$$

(6)

The growth of microcracks can be described as nucleation and propagation of microcracks

$$\left(\frac{\partial C_d}{\partial t}\right)_n = \int_0^\infty \frac{n}{n} n \beta_c c^3 dc$$

(7)

$$\left(\frac{\partial C_d}{\partial t}\right)_g = \int_0^\infty 3n \beta_c c^3 \dot{c} dc$$

(8)

The above formula shows that the change of crack density is caused by the nucleation and propagation of crack characteristic scale. When the rock material is under tension, the upper and lower surfaces of the crack perpendicular to the load direction are separated, which is a typical tensile failure.
3.2. Stress-strain curve of cyclic impact of granite specimen
The stress-strain curve of granite specimen under low-speed cyclic impact is shown in Figure 3.

![Stress-strain curve](image)

**Figure 3.** Stress-strain curve under 0.09MPa accelerated gas pressure

It can be seen from the figure that the single impact process of granite specimen can be divided into elastic stage, crack propagation stage and stable deformation stage. Subsequently, due to the limitation of equipment, the data failed, so the data of failure stage was not measured. Under the impact of the first few times, the elastic stage is more obvious, at this time, the number of original crack nucleation is less, the crack expansion and plastic deformation stage is short; the granite is more brittle, with the increase of impact times, the number of cracks in the specimen gradually accumulates, the damage gradually accumulates, resulting in the elastic stage is not obvious, and the plastic deformation increases.

3.3. Typical energy time history curve during low-speed cyclic impact
The typical energy change rate curve of the specimen is shown in Figure 4.

![Energy time history curve](image)

**Figure 4.** The rate of change of various energies in a single impact

According to figure 4, the evolution of strain energy can be divided into four stages
(1) The variation trend of incident energy and transmission energy is the same in the first 50 ms, and the energy absorption rate is low. Corresponding to the elastic deformation stage, the impact energy is mainly stored in the form of elastic properties.

(2) The results show that the change rate of incident energy and transmission energy increases significantly, and the energy absorption rate increases significantly with the crack propagation; due to the mismatch of wave impedance between the specimen and the compression bar, the incident end face of the specimen generates reflected energy, and the change rate of reflected energy decays rapidly in the later stage. The strain energy is mainly transformed into the surface energy in the process of initial crack formation and initial crack propagation.

(3) In the plastic deformation stage, the number of cracks in this stage no longer increases obviously, but the crack propagates stably under the action of high stress, the energy absorption rate remains stable, and the strain energy mainly exists in the form of surface energy of crack propagation.

(4) In the process of stress decay, the tensile stress on both sides of the crack decreases, the total number of the extended cracks decreases, and the energy absorption rate decreases.

In order to analyze the damage characteristics of granite under cyclic impact more comprehensively, the energy dissipation of granite specimen is analyzed. The results of absorbed energy, reflected energy and transmitted energy in the process of 8 impacts are calculated, as shown in Table 1.

Table 1. Energy statistics under 0.09 mpa accelerated air pressure cyclic impact

| Impact number | Strain energy/J | Reflected energy/J | Transmission energy/J | Incident energy/J |
|---------------|-----------------|-------------------|----------------------|------------------|
| 1             | 26.78           | 1.22              | 88.71                | 116.73           |
| 2             | 29.77           | 1.35              | 97.34                | 128.47           |
| 3             | 30.74           | 1.22              | 87.91                | 119.89           |
| 4             | 37.79           | 2.56              | 82.40                | 122.76           |
| 5             | 39.00           | 2.69              | 83.96                | 125.66           |
| 6             | 40.83           | 2.45              | 88.76                | 132.06           |
| 7             | 40.28           | 2.47              | 87.58                | 130.34           |
| 8             | 42.29           | 3.49              | 78.72                | 124.51           |

Accelerated gas pressure instability during the impact process caused a certain degree of dispersion of incident energy, so it is more reasonable to compare the proportions of strain energy, reflected energy, transmission energy and incident energy, which is:

\[
\varphi_d = \frac{W_d}{W_i} \tag{9}
\]

\[
\varphi_r = \frac{W_r}{W_i} \tag{10}
\]

\[
\varphi_t = \frac{W_t}{W_i} \tag{11}
\]

Where: \( \varphi_d, \varphi_r, \varphi_t \) are the proportions of strain energy, reflected energy, and transmission energy in the incident energy of a single impact; \( W_d, W_r, W_t, W_i \) are strain energy, reflected energy, transmission energy, and incident energy, respectively.
Table 2. Energy ratio under the condition of 0.09mpa accelerated air pressure cyclic impact

| Impact number | Strain energy ratio/% | Reflected energy ratio/% | Transmission energy ratio/% |
|---------------|-----------------------|-------------------------|---------------------------|
| 1             | 22.95%                | 1.05%                   | 76.00%                    |
| 2             | 23.17%                | 1.06%                   | 75.77%                    |
| 3             | 25.64%                | 1.02%                   | 73.33%                    |
| 4             | 30.79%                | 2.09%                   | 67.12%                    |
| 5             | 31.04%                | 2.14%                   | 66.82%                    |
| 6             | 30.92%                | 1.86%                   | 67.22%                    |
| 7             | 30.91%                | 1.90%                   | 67.19%                    |
| 8             | 33.97%                | 2.81%                   | 63.22%                    |

Figure 5 shows the proportions of strain energy, reflected energy, transmitted energy and incident energy during cyclic impact.

During the impact process, the transmitted energy ratio is the largest, about 60%-80% of the incident energy, which increases with the increase of the number of impacts; the strain energy ratio is 20%-35%, which increases with the increase of the number of impacts; the reflected energy is relatively low about 1%-3%, and the dispersion is relatively large. The analysis shows that with the increase of the number of impacts and the accumulation of strain energy, the internal original cracks are activated and the number increases steadily; at the same time, the wave impedance decreases, which enhances the energy absorption of the specimen, and the proportion of strain energy absorption increases; The increase in the number of stress waves also increases the reflection of the stress wave, resulting in a significant increase in the proportion of reflected energy. Since the reflected energy is relatively small as a whole, the unevenness of the increase in the number of cracks is greatly affected, resulting in large fluctuations in the single reflection energy.

The fitting analysis of the energy absorption rate and the total accumulated strain energy is shown in Figure 6.
Figure 6. Fitting relationship between energy absorption rate and accumulated strain energy:

It can be seen from the figure that the absorption rate of strain energy increases with the accumulation of incident energy, which is approximately a linear growth law and has a strong correlation. The expression is:

$$\varphi_3 = 0.22514+4.11448 \times 10^{-4} \ W_I \ (R^2=0.83895)$$

Where: $\varphi_3$ is the absorption rate of strain energy, and $W_I$ is the total accumulation of strain energy.

Conclusion:

This paper studies the dynamic characteristics and energy dissipation of rocks under cyclic impact conditions, and analyzes the damage rules of the specimens in combination with damage theory.

The main conclusions are as follows:

1. Under the action of cyclic impact, the main failure mode of granite specimens is axial tensile cracking.
2. With the increase of the number of impacts, the original cracks in the specimens form damage nuclei and continue to expand. The elasticity of the specimens decreases and the plasticity increases.
3. As the internal damage of the specimen accumulates, the proportion of transmitted energy gradually decreases, which is in a linear relationship with the cumulative amount of impact energy; the proportion of strain energy and reflected energy increases in a linear relationship with the cumulative amount of impact energy.

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