
Analysis of Energy Properties and Failure Modes of Heat-Treated Granite in Dynamic Splitting Test

Reference

ABSTRACT
Dynamic Brazilian disc (or splitting) tests were carried out to study the characteristics of energy dissipation and failure behavior of heat-treated granite under impact loading. Six groups of granite samples were treated at the temperatures of 25°C, 100°C, 300°C, 500°C, 700°C, and 900°C, respectively. Each group of heat-treated samples was tested with three impact velocities of 5.4, 7.7 and 13.7 m/s in a modified split Hopkinson pressure bar. An average change rate of incident energy (ACRIE) was proposed to characterize the loading rate effect. The effects of treatment temperature and ACRIE on the energy dissipation and the failure patterns of samples under impact loading were investigated. The results show that the energy dissipation of the granite decreases with the increase of treatment temperature but increases with the increase of the ACRIE. A rise in treatment temperature or ACRIE may lead to smaller size and greater number of sample fragments. The effect of treatment temperature becomes more obvious as the ACRIE increases. The energy utilization ratio of the granite is generally less than 30 % and has an opposite effect when compared to the loading rate. In addition, the dynamic tensile strength of the samples increases almost linearly with the transmitted wave energy. These studies also indicate that the resistance of rock against tensile failure can be well characterized from the perspective of energy dissipation.

Keywords
granite, thermal treatment, dynamic splitting, energy dissipation, tensile failure

Nomenclature

\[ c_0 = \text{ultrasonic P-wave velocity of sample before heating} \]
\[ c_1 = \text{ultrasonic P-wave velocity of sample after heating} \]
\[ D = \text{thermal damage of sample} \]
\[ V_0 = \text{impact velocity of projectile} \]
\[ W_i = \text{energy of incident stress wave} \]
\[ W_i' = \text{average change rate of incident energy} \]
invented by Kolsky (1953), is an ideal and reliable loading tech-

development of new cracks

W_k = kinetic energy carried by the ejected fragments

W_o = energy consumption

ε_v = strain signal of incident wave

ε_r = strain signal of transmitted wave

ξ = specific energy absorption

η = energy utilization ratio

τ = width of incident pulse

ACRIE = average change rate of incident energy

CT = computer tomography

ISRM = International Society for Rock Mechanics

SEM = scanning electron microscopy

SHPB = split Hopkinson pressure bar

Introduction

Rock is a heterogeneous brittle material containing crystals as well as defects such as pores, cracks, and grain boundaries at the mi-
croscopic scale (Zhou 2010). Its physical and mechanical proper-
ties are quite different under different engineering conditions
such as the excavation of deep rock mass, the disposal of
high-level radioactive wastes, and post-disaster reconstruction
of tunneling projects. All of these differences are related to the
thermodynamic properties of rock. As such, the dynamic
tests on rock samples subjected to different temperature treat-
ments can well disclose the change of rock damage mechanical behaviors under complex geological conditions (Li 2014).

The split Hopkinson pressure bar (SHPB) system, which was
invented by Kolsky (1953), is an ideal and reliable loading tech-
nique to measure the dynamic properties of rock under a middle-
high strain rate. Over the past decades, the SHPB has
been widely used in the study of material dynamic properties,
and many research results have been acquired (Zhao and Li
With the dynamic force balance achieved by the pulse shaping
 technique, it was proved that in a dynamic Brazilian disc (or splitting) test, the time-varying dynamic forces on both ends of the sample were almost identical (Dai et al. 2010; Dai and Xia
2010). In order to obtain the crack initiation and propagation process in dynamic splitting tests, Zhou et al. (2014) used a high-speed camera to monitor the fracturing processes in the Brazilian disc test. Scanning Electron Microscopy (SEM) and the X-ray Computer Tomography (CT) were also adopted to observe the microcracks of sandstone and mortar samples exposed to high temperature (Huang and Xia 2015; Yao et al. 2016; Yao et al. 2017). As a result of improvements in the shape of the sample, the ring sample (Li et al. 2016), and the semidisc sample (Dai, Xia, and Luo 2008; Dai et al. 2013; Xu et al. 2016) were used to measure the tensile strength of the rock. Chen et al. (2009) proposed an improved SHPB technique with a notched semicircular bending sample to measure the dynamic fracture parameters and investigated the fracture mechanics of brittle materials with coarse grains. Wu, Chen, and Xia (2015) focused on the dynamic tensile failure of rocks under static pre-tension, and found that dynamic tensile strength decreased with the increase of the pre-tension stress.

The deformation to failure of rock is an irreversible process of energy dissipation. A new tendency is to study the mechanical properties of rock material purely from the perspective of energy. Xie et al. (2009) regarded that the failure of rock was the result of energy dissipation and energy release. They developed a structural failure criterion for rock. Xu and Liu (2013) experimentally studied the relationship between the fractal dimension, average fragment size, and energy dissipation of marble and found that the deformation and fracturing process of marble could be reasonably reflected from the standpoint of energy. So far, studies on the dynamic tensile strength of rock from the perspective of energy dissipation are rarely found in the public literature.

In this study, the dynamic splitting tests are carried out on thermally treated granite by using a modified SHPB. Then, an average change rate of incident energy (ACRIE) is proposed to characterize the loading rate effect. The effects of treatment temperature and ACRIE on the energy dissipation and the failure modes of samples are investigated. Finally, the energy dissipation characteristics of the granite during the impact loading condition and the relationship between the splitting strength and the energy variation are discussed in detail.

Dynamic Splitting Test of Heat-Treated Granite

PREPARATION OF SAMPLE

The selected rock was Huashan granite from the Shanxi Province in China. It belongs to the gray biotite granite with a density of 2,600 kg/m³. The moisture content is 0.57 % and the average uniaxial compressive strength is 140 MPa. The main mineral compositions include microcline (41 %), plagioclase (27 %), quartz (22 %), and biotite (7 %) among others. According to the assumption of stress uniformity in the SHPB test, the ratio of height to diameter was set as 0.5 (Li 2014; Zhou et al. 2012).
Thus, the samples were fabricated into the short cylinder of the size $\Phi 50 \times 25$ mm in laboratory. The samples were carefully ground by a grinding machine to ensure the parallelism between the top and the bottom surfaces was less than 0.05 mm. The machining precision and basic dimensions of the granite samples satisfied the standard suggested by the International Society for Rock Mechanics (ISRM).

**LAYOUT OF THERMAL TREATMENT**

In the present study, six groups of samples were prepared including one obtained at room temperature (25°C) and the other five treated at 100°C, 300°C, 500°C, 700°C, and 900°C, respectively. The thermal treatment was conducted in a servo-controlled electrical furnace at a rate of 10°C/min. As soon as the temperature reached a specified value in the furnace, the temperature was maintained for 4 hours. The samples were then cooled down to room temperature in the electric furnace, and they were kept the same position as heating. The whole process lasted approximately 10 hours. All six groups were tested with three different impact velocities (5.4, 7.7, and 13.7 m/s), so 54–90 samples were used to ensure at least three effective data for each case.

**PRINCIPLE OF DYNAMIC SPLITTING TEST**

Due to operational difficulties in direct tensile tests, indirect methods serve as convenient alternatives to measure the tensile strength of rock-like materials, such as the Brazilian disc test and three-point bending test. In recent years, the SHPB has been extensively used to study the tensile behavior of rock (Zhang and Zhao 2014; Wang, Li, and Xie 2009; Dai et al. 2010; Li et al. 2016; Wu, Chen, and Xia 2015; Zhou et al. 2014; Wang and Hao 2017).

**Fig. 1** shows the modified SHPB system with a variable cross-section. This SHPB is mainly composed of a bar subsystem, a loading subsystem, and a testing subsystem. In the SHPB system, the lengths of the striker bar, incident bar, and transmitted bar are 400, 2,400, and 1,200 mm, respectively. The wave velocity of the bars is 5,172 m/s, and the elastic modulus is 210 GPa.

During the test, the granite sample was sandwiched between the incident bar and transmitted bar, as shown in **Fig. 2**. The incident wave, which is launched when the strike bar (or projectile) impacts the incident bar at a velocity of $V_0$, propagates along the incident bar. When the incident wave arrives at the interface between bar and sample, the reflected wave and the transmitted waves are generated. Typical voltage signals on the incident and transmitted bars are recorded by the strain gauge (see **Fig. 3**). Based on the assumption of the SHPB test, the stress in the sample soon becomes uniform after the stress waves reflect back and forth.
forth two to three times, indicating that the sample is in a state of dynamic stress equilibrium, as shown in Fig. 4. It has been noticed that the time-varying stresses on both sides of the sample match well with each other before the peak point is reached during the dynamic loading (Dai and Xia 2010).

According to the one-dimensional stress wave theory, the forces at the two loading ends of the sample are calculated as the following:

\[ F_1(t) = E_0 A_0 (\varepsilon_i(t) + \varepsilon_r(t)) \]  
\[ F_2(t) = E_0 A_0 \varepsilon_r(t) \]  

The average loading force for the two ends of the sample is the following:

\[ F(t) = \frac{F_1(t) + F_2(t)}{2} = \frac{E_0 A_0}{2} (\varepsilon_i(t) + \varepsilon_r(t) + \varepsilon_i(t)) \]  

where \( A_0 \) and \( E_0 \) denote the area and the elastic modulus of the bars, respectively.

According to the static Brazilian test, the formula for tensile strength of disc sample is the following:

\[ \sigma_t(t) = \frac{2F(t)}{\pi dL} \]  

where \( d \) and \( L \) represent the diameter and the thickness of the sample, respectively.

Provided that a quasistatic state has been achieved in the sample during the dynamic Brazilian test, the maximum stress \( \sigma_t(t) \) at the center of the sample can be considered as the dynamic splitting strength, \( f_{sd} \) (Li 2014; Wu et al. 2009).

Analysis of Test Results

FORMULA OF ENERGY DISSIPATION

The dynamic tensile strength of Huashan granite can be similarly obtained via the analytical solution of elastic mechanics for the static Brazilian test, but the stress state in the dynamic Brazilian tensile test is obviously different from the static one. This is because the propagation and interaction of the stress wave under a high loading rate couple with the nonlinearity of constitutive behaviors (Wu et al. 2009; Zhou 2004). Therefore, the assessment of the resistance of rock to tensile failure from the perspective of energy dissipation is better than that from the index of dynamic splitting strength.

Let \( W_i(t) \), \( W_d(t) \), and \( W_t(t) \) denote the energy of incident wave, reflected wave, and transmitted wave, respectively. The dissipated energy of the sample, \( W_s(t) \), can be written as the following (Li 2014):

\[ W_s(t) = W_i(t) - W_r(t) - W_t(t) \]  

in which,

\[ W_i(t) = E_0 A_0 \varepsilon_0 \int_0^t \varepsilon_i^2(t) dt \]  
\[ W_r(t) = E_0 A_0 \varepsilon_0 \int_0^t \varepsilon_r^2(t) dt \]  
\[ W_t(t) = E_0 A_0 \varepsilon_0 \int_0^t \varepsilon_t^2(t) dt \]  

where \( \varepsilon \) is the velocity of the elastic longitudinal wave in bars and \( \tau \) is the width of the incident pulse.

The dissipated energy of the sample mainly has three components: the energy \( W_{de}(t) \) for the extension of existing cracks and the initiation of new cracks; the kinetic energy \( W_{ke}(t) \) carried by the ejected fragments, and the rest for energy consumption \( W_{re}(t) \). Referring to Zhang et al. (2000), \( W_{de}(t) \) is about 95% of \( W_s(t) \), and they have a linear relationship.

SHAPE OF ENERGY EVOLUTION CURVE

Fig. 5 shows the relationship between the energy components and time for the granite sample treated at the temperature of 100°C. Obviously, the process of energy dissipation can be divided into four phases:

- The compaction phase: the slope of the energy dissipation curve is very small. Microcracks are gradually closed by impact compression, which requires less energy in this process.
- The elastic deformation phase: the energy dissipation increases rapidly, during which the sample absorbs a large amount of energy for elastic energy storage and crack initiation (Sufian and Russell 2013).
- The accelerated nonelastic deformation phase: the microcracks grow and coalesce. Although the energy absorbing rate gradually decreases, the corresponding amount of energy increases.
The destruction phase: the curve of energy dissipation almost remains horizontal, implying that there is no increase in energy absorption, and the sample thoroughly fails. The incident, reflected, transmitted, and dissipated energy all reach the maximum values, denoted as $W_{\text{imax}}$, $W_{\text{rmax}}$, $W_{\text{tmax}}$, and $W_{\text{smax}}$, respectively.

Effect of Thermal Damage on Energy Dissipation

In general, the energy dissipation characteristics of thermally treated granite in dynamic Brazilian tests are mainly determined by the thermal damage and the incident energy. Fig. 6 gives the SEM photos of the sample slices. It shows that the thermal damage increases with the increase of temperature. Fig. 6a, for instance, shows that there are many initial microcracks in the sample slice at room temperature. The intercrystalline and intracrystalline cracks can be detected in the samples heat-treated at 300°C and 500°C (see Fig. 6b and 6c). After the 700°C treatment, as shown in Fig. 6d, the sample damage becomes more severe, and macroscopic secondary fissures appear on the slice surface. Fig. 6e illustrates that the 900°C treatment sample exhibits ductile failure with dimples.

Ultrasonic measurements on each sample were completed using the contact transmission technique before and after the thermal treatment. Signals from the wave generator were transmitted to the sample at the upper end via a sensor and picked up by a second sensor attached to the lower end of the sample (see Fig. 7). The signals were then digitized and saved in a computer for obtaining the ultrasonic P-wave velocity. A constant pressure was systematically applied to ensure a tight contact between the sample and the transducers. Vaseline was chosen as the coupling agent between samples and transducers in order to transmit the ultrasonic energy to the samples.
The thermal damage can be defined as the following:

\[ D = 1 - \frac{c_1^2}{c_0^2} \]  

in which \( c_0 \) and \( c_1 \) are the ultrasonic P-wave velocity of the sample before and after thermal treatment, respectively.

Table 1 lists the test data of all granite samples. Fig. 8 shows that the dissipated energy decreases with the increase of thermal damage. Their downward trends are almost identical. The dissipated energy of the sample under impact loading decreases sharply when the thermal damage approaches 0.9. This is because the energy dissipation for the initiation of new cracks is much higher than that for the extension of existing cracks (Li 2014). Under severe thermal damage, cracks are massive in the sample, and the impact-induced failure swiftly finishes along the cracking direction.

EFFECT OF ACRIE ON ENERGY DISSIPATION AND SAMPLE FAILURE

The curve of the dissipated energy versus the impact velocity of projectile for the thermally treated sample is presented in Fig. 9. A continuous increase in the energy dissipation is observed with the increase of the impact velocity at the same temperature. This is the obvious effect of loading rate. For example, the dissipated energy increases by 80% for the 500°C sample when the impact velocity increases from 7.7 m/s to 13.7 m/s. In fact, the amount of incident energy is determined by the impact velocity, which has a major influence on the change of energy dissipation of the sample.

In dynamic Brazilian disc tests, the history of the tensile stress wave is usually used to substitute the loading history (Yin et al. 2015). The feasibility lies in the fact that there exists a linear segment before the peak of tensile stress. The slope is taken as the loading rate (\( \dot{\sigma} \)), as shown in Fig. 10. However, this apparent loading rate is significantly affected by the splitting strength of rock (Li 2014). In order to eliminate this influence, the terminology of ACRIE, \( \dot{W}_i \), is proposed herein to characterize the loading rate effect. This ACRIE is completely independent of the splitting strength. From the typical curves of incident energy versus time in Fig. 11, the corresponding values of \( \dot{W}_i \) for the three impact velocities are calculated as 0.05, 0.25 and

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**TABLE 1** Results of SHPB dynamic splitting test.

<table>
<thead>
<tr>
<th>No.</th>
<th>( T ) (°C)</th>
<th>( W_i ) (MJ/s)</th>
<th>( c_0 )</th>
<th>( c_1 )</th>
<th>( W_{max} ) (J)</th>
<th>Average of ( W_{max} )</th>
<th>( W_{max} ) (J)</th>
<th>Average of ( W_{max} )</th>
<th>( \xi )</th>
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<td>WP1-1</td>
<td>25°C</td>
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<td>46.088</td>
<td>8.162</td>
<td>8.166</td>
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<td>WP1-5</td>
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<td>0.25</td>
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<td></td>
<td>46.994</td>
<td>7.555</td>
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<td></td>
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<td>246.956</td>
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<td>3,049</td>
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<td>3,472</td>
<td>10.552</td>
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<td>3,049</td>
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<td>3,049</td>
<td>248.668</td>
<td>20.124</td>
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1.54 MJ/s, respectively. Thus, the ACRIE has evident advantages: it can well embody the intensity of impact loading, and the adoption of a straight-line slope effectively reduces the artificial error in the determination of the starting point of the incident wave. Therefore, it accurately reflects the influence of the incident wave on the energy dissipation characteristics.

Due to the limitation of dynamic testing technique, the energy dissipation characteristic of rock also has the size effect. In order to reasonably uncover the law of energy dissipation, the specific energy dissipation $\xi$ is chosen as the energy dissipation index. This $\xi$ is the dissipation energy of the rock sample per unit volume (Li, Lok, and Zhao 2005) and is calculated by the following:

$$\xi = \frac{W_{\text{max}}}{V}$$  \hspace{1cm} (8)

where $V$ is the volume of sample.

The relationship between the specific energy dissipation and the ACRIE is shown in Fig. 12. It is seen that the specific energy dissipation of the samples is concentrated in the range of 0.3–3.0 J/cm$^3$ in this test. At the same temperature, the specific energy dissipation increases with the increase of the ACRIE, but the increase rate tends to diminish. When the sample size remains

<table>
<thead>
<tr>
<th>No.</th>
<th>T (°C)</th>
<th>$W_i$ (MJ/s)</th>
<th>$c_0$</th>
<th>$c_1$</th>
<th>$W_{\text{max}}$ (J)</th>
<th>Average of $W_{\text{max}}$</th>
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constant, the specific energy dissipation of the samples increases accordingly.

From the macroscopic view, the heat-treated sample finally breaks into two halves when subjected to the subsequent impact loading. In general, tensile and shear failures are two main failure modes in the dynamic splitting test. The shear failure is partially caused by the external thrust from the incident/transmitted bars after the sample is broken. As the ACRIE increases, the micro-cracks hardly have sufficient time to propagate along the weakest interface due to the rapid loading, resulting in the multiple fracturing (see Fig. 13). Besides, the shear failure zones at the loading ends of the Brazilian disc are extended (Yao et al. 2016), and the corners of the sample halves are broken into wedge-shaped pieces due to bending and shearing (Zhou et al. 2014).

**EFFECT OF TREATMENT TEMPERATURE ON ENERGY DISSIPATION AND SAMPLE FAILURE**

On the micro-scale, both the loss of water and the phase transition of quartz (Heap et al. 2013; Peng and Redfern 2013) due to high temperature can lead to the damage of samples, and thus the velocity of ultrasonic P-wave has corresponding variation (Chaki, Takarli, and Agbodjan 2008). Fig. 14 shows the relationship between the dissipated energy and treatment temperature. At the same ACRIE, the dissipation energy decreases with the increase of treatment temperature. There are differences in the variation trends under different ACRIEs. For example, at the ACRIE of 0.05 MJ/s, the energy dissipation for the 900°C treatment sample is 1.78 J less than that at room temperature (61% reduction). For the ACRIE of 0.25 MJ/s, the corresponding reduction is 5.28 J or
65% (refer to Table 1). Therefore, the increase of the ACRIE may lead to a more significant effect of treatment temperature on the variation of dissipated energy.

For a fixed ACRIE (for example, 0.05 MJ/s), the failure patterns of the samples transform from diametrically fracturing to multiple fragments with the increase of the treatment temperature (see Fig. 15), and even triangular crushed zones were formed at the two loading ends of the disc sample. In particular, the number of sample fragments significantly increases at the temperature of 700°C or above (see Fig. 15e and 15f), which can be attributed to the severe thermal damage of the sample (see Fig. 6d and 6e).

**UTILIZATION RATIO OF INCIDENT WAVE ENERGY**

During the SHPB test, a pulse shaper was adopted to eliminate the oscillation of incident wave due to the dispersion effect. Generally, the pulse shaper is made of a thin sheet of circular copper or soft rubber, sticking to the free end of the incident bar for waveform correction in order to achieve the desired incident wave (Gerlach et al. 2011; Frew, Forrestal, and Chen 2002). A soft rubber with a diameter of 10 mm and a thickness of 3 mm was employed as the pulse shaper through the present multiple trial tests (see Fig. 16).

Since the deformation of the pulse shaper absorbs energy during impact loading, the kinetic energy carried by the projectile is not completely converted into the incident energy. Additionally, when the incident wave arrives at the interface between the bar and the sample, a large portion of the wave energy is changed into the reflected wave energy and transmitted wave energy. Only a small part is used to break the sample. For convenience, a concept of energy utilization ratio $\eta$ is defined as the following (Zhang et al. 2000):

$$\eta = \frac{\text{Utilized energy}}{\text{Total energy}}$$
The energy utilization ratio versus the treatment temperature is plotted in Fig. 17. It is noted that the energy utilization ratio of the dynamic Brazilian disc test on the Huashan granite is less than 30%. It decreases with the increase of treatment temperature. Energy analysis shows that the energy dissipation of the thermally treated sample also has a strain-rate effect. That is, energy dissipation increases with the increase of ACRIE. On
the contrary, the energy utilization ratio decreases with the increase of ACRIE.

**RELATION OF SPLITTING STRENGTH AND TRANSMITTED WAVE ENERGY**

The dynamic strength is an important index to measure the mechanical properties of the rock material. Since the deformation and failure of rock is a process of energy dissipation and energy release (Zhou, Yang, and Zhang 2009), the dynamic tensile behavior of rock can be described from the energy perspective. The relationship between the dynamic splitting strength and the transmitted wave energy is shown in Fig. 18, which indicates that the dynamic splitting strength increases almost linearly with the energy of the transmitted wave. Also, the strain rate has a significant influence on the splitting strength of the thermally treated samples.

**Conclusions**

In this study, the dynamic Brazilian disc tests were carried out on the granite heat treated at different temperatures. The concept of ACRIE was then proposed to characterize the loading rate effect. The influences of treatment temperature and ACRIE on energy dissipation and failure modes of the granite samples were analyzed. The following conclusions can be drawn based on these results and observations:

1. The energy dissipation characteristics of the granite are significantly affected by the treatment temperature and the ACRIE. At the same temperature, the dissipated energy increases with the increase of ACRIE. For a given impact velocity, the dissipated energy of the sample decreases with the increase of treatment temperature.

2. The failure pattern of the granite samples in dynamic splitting tests is closely related to the treatment temperature and the ACRIE. The increase in either of these quantities would lead to a smaller size and greater number of sample fragments. With the increase of ACRIE, the effect of treatment temperature becomes more obvious.

3. The energy utilization ratio is generally less than 30% in the dynamic Brazilian disc tests on the Huashan granite. It is in negative correlation with the ACRIE (or impact velocity). Furthermore, the splitting strength of the granite increases almost linearly with the energy of the transmitted wave to some extent.

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**References**


