DYNAMIC FRACTURE AND ENERGY CONSUMPTION CHARACTERISTICS OF COAL-SERIES SANDSTONE AFTER HEAT TREATMENT

by

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Original scientific paper
https://doi.org/10.2298/TSCI180612248L

In this paper, the dynamic loading tests of sandstone after heat treatment at 25-800 °C are carried out by using the split Hopkinson pressure bar test system. Combined with the theory of energy dissipation, the dynamic fracture and energy consumption characteristics of coal-series sandstone are systematically studied. The test results illustrate that the dynamic fracture and energy consumption characteristics of sandstone are mainly related to the changes of internal moisture and cementing materials.

Key words: *heat treatment, coal-series sandstone, strain rate, surface energy*

Introduction

The problems of dynamic rock damage after heat treatment is widely involved in coal underground gasification, coalbed methane mining and underground space reconstruction after the fire. To fundamentally clarify the characteristics of rock failure under high temperatures and dynamic loads, it is necessary to carry out a series of work from the energy perspective. At present, the influence of temperature on the mechanical properties of rock is one of the hot research directions in the field of rock mechanics. Through a series of experiments, scholars studied the effect of temperature on the physical and mechanical properties of rocks. Studies have shown that temperature can significantly change the physical properties of rocks, such as increasing the permeability and bulk density of rocks*, etc.* [1, 2]. Physical properties can further alter the mechanical properties of the rock, for example, increased heating temperature can significantly decrease the elastic modulus and increase the compression and tensile strength [3, 4]. In recent years, with the increase of rock thermodynamics problems, some scholars have begun to try to study the rock mechanics under the combined action of temperature and impact load. Ahmed *et al*. [5] performed a thermal cycle of 50-200 °C on the rocks of the Khewr Gorge in Punjab, Pakistan in increment of 50 °C. Then the Erudite resonance frequency meter was used to measure the Q factor and resonance frequency. The results showed that the thermal cycles reduced the dynamic Young's modulus and Q factor, while the damping ratio and loss factor increased with the increase of thermal cycle. Yin *et al.* [6] found that the temperature-treated stress-strain curves changed from brittle to viscoelastic with increasing temperature. Wang *et al*. [7] found that the number of micro-cracks and micro-pores in the granite was reduced after treatment at 200 °C.

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With the same impact load, the average value of the peak stress of the samples after treatment at 600 °C is much smaller than the average value after treatment at 200 °C and 400 °C.

Although many scholars have studied the dynamic fracture characteristics of rocks after heat treatment [7], but the research results of the energy dissipation characteristics and the dynamic arrangement characteristics of heat-treated rocks from the perspective of energy theory have rarely been reported. In this paper, the SHPB test system is used to carry out the impact loading tests on coal-series sandstone after heat treatment at 25-800 °C, to clarify the block distribution characteristics, and to shown thatthe energy dissipation characteristics during the destruction process of sandstone are systematically studied to provide reference for deep coal mining and coal underground gasification engineering.

Test overview

Sample preparation and test equipment

The rock material used in this study was taken from the roof of a mining face in Xuzhou, and it was processed into disc specimens with a diameter of 50 mm and a height of 25 mm by drilling, cutting and grinding. The samples were heated to 100-800 °C (with interval of 100 °C) by a heating device (MTS 653 electric heating furnace) at a heating rate of 5 °C/min. The samples were cooled to room temperature in a heating furnace after keeping for 2 hours at the and highest temperatures. The samples were store in a constant temperature drying oven. The 5-7 samples were prepared for each temperature condition.

The dynamic testing was conducted using a split Hopkinson pressure bar (SHPB) system, as shown in fig. 1. The structural composition and working principle are described in the literature [8].

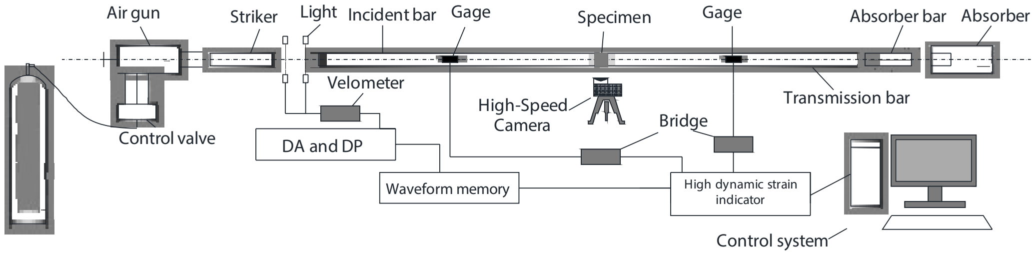

Figure 1. Separate Hopkinson pressure bar test system

Test plan and loading conditions

In this study, we mainly investigate the influence of temperature on sandstone damage and its energy consumption characteristics. Therefore, it is necessary to ensure that the strain rate of the samples is as same as possible. In the tests, each group of samples was tested several times under the impact pressure of about 0. 4 MPa, and the test results under similar strain rate were selected for analysis. Figure 2 shows the loading strain rate of sandstone after different heat treatment temperatures. It can be seen that the strain rate of sandstone under different heat treatment conditions is basically around 48 s^{-1}. Therefore, the strain rate can be considered to be the same. Figure 3 shows the waveform of sandstone under impact load. It can be seen from the figure that the incident wave has no obvious lateral vibration, and the superimposed sum of incident wave and reflected wave almost coincides with the transmitted wave, indicating that the tests satisfy the conditions: 1-D stress propagation and the stress uniformity.

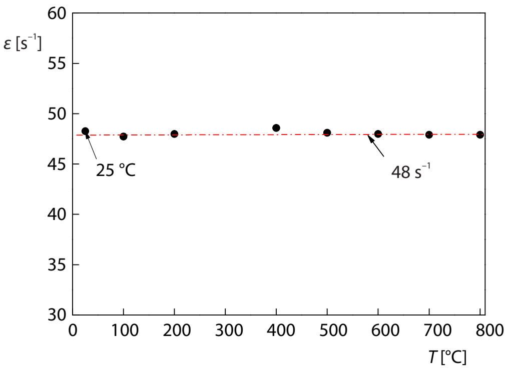

Figure 2. Sample loading strain rate at different temperatures

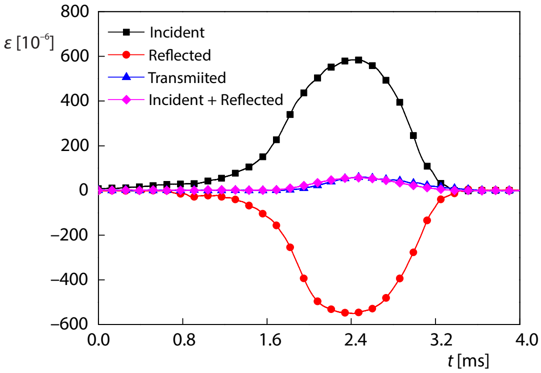

Figure 3. Typical sandstone impact loading waveform

Dynamic failure characteristics of coal measures sandstone after heat treatment

Macroscopic failure pattern and blockiness distribution of sandstone

Figure 4 shows the failure morphology of sandstone after heat treatment at room temperature to 800 °C. It can be seen from the diagram that the damage morphology of the specimens after impact load is mainly the splitting cylinder. As the temperature increases, the number of small fragments also increases as the first characteristic decreases. When the temperature is 500 °C, the average damage volume of the fragments is the largest.

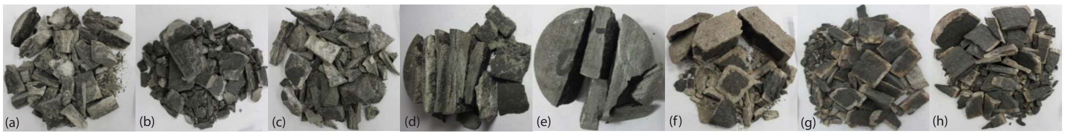

Figure 4. Sandstone failure morphology at different temperatures; (a) 25 °C, (b) 100 °C, (c) 200 °C, (d) 400 °C, (e) 500 °C, (f) 600 °C, (g) 700 °C, and (h) 800°C

With the aid of the damage particle size of the sandstone, the sandstone samples at different temperatures were divided into 8 groups by using the grading sieves: 0-2.5 mm, 2.5-5.0 mm, 5.0-8.0 mm, 8.0-10.0 mm, 10.0-12.0 mm, 12.0-15.0 mm, 15.0-20.0 mm, and 20.0-50.0 mm. After the screening was completed, the particle size mass of each group was weighed by a high-sensitivity electronic scale, and the mass percentage of fragments of each group was calculated:

$$M_{sn} = \frac{m_n}{M} \tag{1}$$

where M_{sn} is the proportion of fragments at a specific granularity, m_n – the mass of fragments of a specific particle size, and M – the total mass of the fragments.

The average particle size of sandstone under impact load after different heat treatments can expressed:

$$r = \sum_{n=1}^{8} M_{sn} d_{vn} \tag{2}$$

where r is the average particle size and d_{vn} – the average particle size of the range of particle size of each group, which means the average of the maximum particle size and the minimum particle size of the range.

Table 1 shows particle size distribution and average particle size of sandstone after impact damage at different heat treatment temperatures. It can be seen from the table that: when the temperature is 400 °C and 500 °C, the amount of debris less than 12 mm is negligible. With the temperature of 500 °C as the critical value, the small particle sizes of fragments decrease first and then increase with the increase of temperature, while the large particle sizes of fragments increase first and then decrease. As the temperature changes, the average particle size change of the smaller particle size is the same.

Table 1. Sandstone particle size distribution and average particle size under different heat treatment temperatures

T [°C]	M [g]	M_{sn} [%]								r [mm]
		1	2	3	4	5	6	7	8	
25	129. 90	4. 88	4. 28	9. 53	5. 69	6. 18	11. 09	19. 26	39. 09	22. 34
100	127. 87	3. 74	4. 31	12. 2	6. 65	11. 3	8. 98	10. 89	41. 93	22. 18
200	127. 43	2. 71	2. 88	4. 23	9. 65	9. 05	5. 42	10. 56	55. 5	19. 13
400	128. 47	0	0	0	1. 32	2. 53	2. 40	3. 96	89. 79	13. 03
500	125. 07	0	0	0	0	0	9. 16	3. 57	87. 27	12. 56
600	126. 73	1. 89	3. 78	6. 27	5. 06	5. 69	9. 61	18. 64	49. 06	17. 78
700	124. 27	4. 06	4. 01	1. 01	10. 62	12. 45	18. 09	22. 25	27. 51	21. 18
800	124. 27	5. 47	6. 52	5. 48	10. 64	11. 22	19. 42	18. 83	22. 42	24. 19

Fractal characteristics of macroscopic failure of sandstone

According to the fractal theory, the fractal characteristics of samples after failure are analyzed. The method of mass-equivalent size is used to find the fractal dimension. The fractional dimension:

$$D = 3 - d \tag{3}$$

where D is the fractal dimension of the fragment and d is the slope of the straight line in the logarithmic co-ordinates of mass and particle size, denoted:

$$d = \frac{\lg \frac{M_R}{M}}{\lg R} \tag{4}$$

with the cumulative mass of fragments, M_R, and the diameter of the particle size, R.

According to tab. 1, the logarithmic relation fitting line between the mass of broken pieces and particle size can be obtained, as shown in fig. 4. The slope d of the straight line under various conditions can be calculated through fig. 5. Figure 6 shows the changing rule of the fractal dimension with the heat treatment temperature. It can be seen that under the same strain rate, the fractal dimension of sandstone after damage decreases firstly and then increases with temperature, and reaches a minimum at a temperature of 500 °C. This indicates that when the strain rate of the samples is the same, the sandstone has the lowest degree of damage at a temperature of 500 °C.

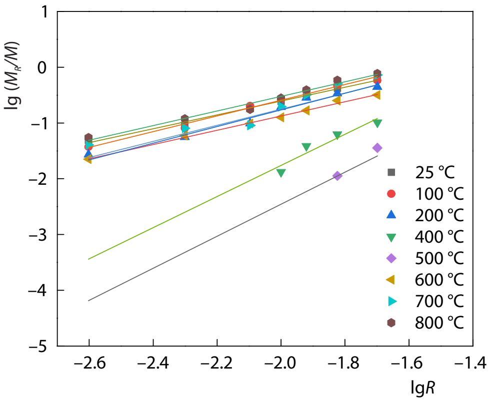

Figure 5. Straight line of mass and particle size logarithm

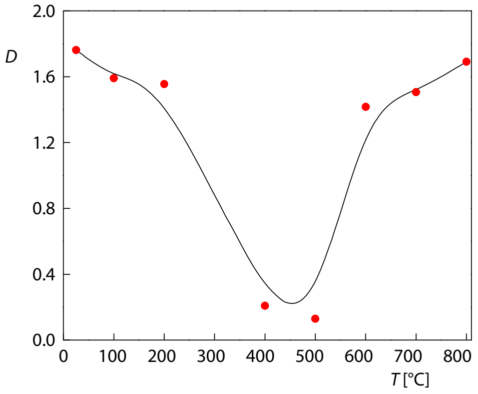

Figure 6. Variation of fractal dimension with temperature

Energy change law of sandstone

The energy change is the root cause of the rock fracture. According to the law of thermodynamics, energy transformation is the essential feature of physical processes, and the destruction of materials is a phenomenon of instability state driven by energy. Here, it is necessary to clarify the fracture mechanism of coal-series sandstone from the perspective of energy.

Calculation method of failure energy of sandstone

Making use of the principle of stress wave, the energy expression form of sandstone impact damage can be written [8]:

$$W = \frac{AC}{E}\int_0^t \sigma^2(t)\mathrm{d}t = ACE\int_0^t \varepsilon^2(t)\mathrm{d}t \tag{5}$$

where A is the cross-sectional area of the pressure bar and equal to 0.196 m^2, E – the elastic modulus of the pressure bar material and equal to 206 GPa, and C – the stress wave velocity, (we take C = 7500 m/s).

From eqs. (4) and (5), the incident energy, denoted as W_I, the reflected energy, denoted as W_R, and the transmitted energy, denoted as W_T, can be expressed:

$$W_{(\mathrm{I,R,T})} = ACE\int_0^t \varepsilon^2{}_{(i,r,t)}(t)\mathrm{d}t \tag{6}$$

where ε represents the strain on the pressure bar, and i, r, and t – the represent incident wave, reflected wave, and transmitted wave, respectively.

From eq. (6), the dissipative energy of the sandstone, denoted as W_L, can be given:

$$W_\mathrm{L} = W_\mathrm{I} - W_\mathrm{R} - W_\mathrm{T} \tag{7}$$

The variation law of sandstone impact damage energy with temperature

According to eq. (6) and eq. (7), the variation law of each energy with temperature is obtained, as shown in fig. 7. It can be seen from fig. 7 that under the same strain rate, the incident energy and the reflected energy are basically unchanged and are maintained at about

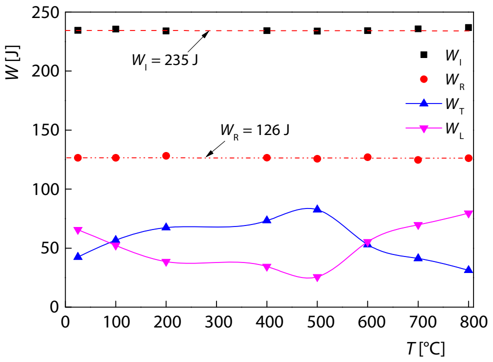

Figure 7. Characteristics of energy changes with temperature during sample impact

235 J and 126 J. As the temperature increases, the inflection point of the change in transmitted energy and dissipated energy is 500 °C. The former characteristic of the change is that first increased and then decreased, while the latter one decreased first and then increased. Specifically, when the heat treatment temperature increased from 25-500 °C, the transmission energy increased from 42.40-82.55 J, which the value almost doubles and the dissipated energy is rapidly decreased from 65.57-25.64 J, with a drop of 60.90%. When the heat treatment temperature increased from 500-800 °C, the change laws of transmitted energy and dissipated energy exchanged. The transmission energy decreased from 82.55-31.23 J and the amplitude was 62.17%. The dissipated energy increased from 25.64-79.54 J, which improved about 2.10 times.

The surface specific energy variation characteristics of sandstone dynamic failure

The dissipated energy of sandstone under impact load is mainly used for the separation of fragments from each other. Therefore, in order to reveal the energy consumption mechanism in the process of sandstone failure, it is necessary to define the characteristics of dissipated energy per unit area on the fracture surface of fragments, which is defined as surface specific energy.

If the fragments within a certain particle size range are spheres within the average radius, then the number of spheres in the unit can be expressed:

$$n_n = \frac{m_n}{4\pi r_n^{\,3} \dfrac{\rho}{3}} \tag{8}$$

where n_n is the number of spheres in the range of size n, m_n – the total mass of the unit sphere, and r_n – the sphere radius of the transformation.

The area of impact fracture surface, denoted as S_ω, can be given:

$$S_\omega = \sum_{1}^{8} 4 n_n \pi r_n^2 - 2\pi r h - 2\pi r^2 \tag{9}$$

where r is the sample radius and h is the sample height.

If the dissipated energy is used to separate the fragments from each other, then the dissipated energy can be expressed:

$$W_L = S_\omega \lambda_\omega \tag{10}$$

where λ_ω is the dissipated energy per unit area.

With a turning point of 500 °C, the surface energy increases first and then decreases. Specifically, when the heat treatment temperature is less than 200 °C, the surface energy does not change much, and the value is basically around 1500. When the temperature increases from 200-500 ° C, the surface energy increases from 1420-5100, which is 2.6 times higher. When the temperature increases from 500-600 °C, the surface energy decreases rapidly, and the amplitude is 52.45%. When the temperature exceeds 600 °C, the surface energy decreases slowly. From figs. 7 and 8, it can be seen that under different temperature conditions, when the dissipated energy is smaller, the surface energy is larger, and this energy consumption characteristic also determines that the sample has a lower degree of damage and a smaller fractal dimension.

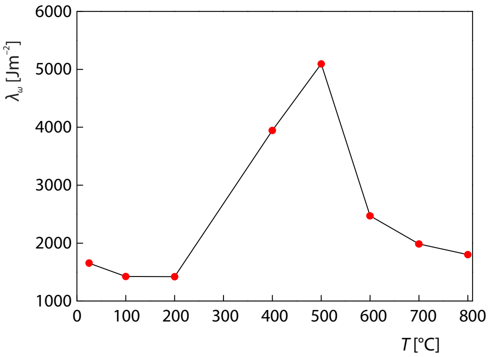

Figure 8. The change of surface energy of the sandstone with different heat treatment temperatures

The change of surface energy of sandstone is closely related to the change of its internal material composition. When the temperature is below 500 °C, with the increase of temperature, the internal moisture gradually evaporates, and the expansion of particles such as quartz increases the compactness inside the sandstone and the friction between the particles. The energy consumption per unit area gradually increases, which means the surface energy is gradually increased. When the temperature exceeds 500 °C, the cementitious materials such as kaolinite in the sandstone are decomposed in [9], and the defects such as internal pores and cracks increase. The cementation between the particles decreases with the increase of temperature. Therefore, when the sample is broken, the dissipation per unit area of the fragments reduces, and the surface energy gradually decreases.

Conclusion

In this work, the SHPB test system was used to carry out the impact loading tests of coal-series sandstone after heat treatment at different temperatures. The block distribution characteristics are obtained by sieving and the energy dissipation characteristics during the failure process are also discussed. Under the same strain rate, the average particle size of the sandstone fragments increases first and then decreases with the increase of temperature, and reaches the peak at 500 °C. The fractal dimension of the fragments is opposite to the variation of the average particle size, indicating that the overall dynamic damage of the sandstone first decreases and then increases. Under the same strain rate, during the process of sandstone failure, as the heat treatment temperature increases, the transmission energy increases first and then decreases, and peaks at 500 °C, while the dissipation energy first decreases and then increases. The calculation method of surface energy of sandstone during the impact damage process is given, and the results show that the sandstone surface energy decreases first and then increases at the same strain rate, and reaches a minimum at 500 °C. The cause of the change is mainly related to the evaporation of internal water and the decomposition of substances such as kaolinite.

Nomenclature

A – cross-sectional area of the bar, [mm^2]
C – stress wave velocity, [ms^{-1}]
D – fractal dimension, [–]
d – slope, [–]
d_{vn} – group average particle size, [mm]
E – elastic modulus, [GPa]
h – sample height, [mm]
M – total mass of the fragments, [g]
M_R – cumulative mass of less then$R$, [g]
M_{sn} – proportion of fragments, [–]
m_n – mass of fragments, [g]
m_n – total mass of the unit sphere, [g]
n_n – number of spheres, [–]
R – particle size, [mm]
r – average particle size, [mm]
r_n – phere radius, [mm]
S_ω – area of impact fracture surface, [mm^2]
$W_{\rm I}$ – incident energy, [J]

W_L – dissipative energy, [J]
W_R – reflected energy, [J]
W_T – transmitted energy, [J]

Greek symbols

ε – strain, [–]
λ_ω – dissipated energy, [Jmm^{-2}]
σ – stress, [MPa]

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Paper submitted: July 12, 2018
Paper revised: September 15, 2018
Paper accepted: November 19, 2018