EFFECT OF STRAIN RATE AND HIGH TEMPERATURE ON THE TENSILE MECHANICAL PROPERTIES OF COAL SANDSTONE

by

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The Split-Hopkinson pressure bar test system with the MTS652.02 high temperature furnace and the 50 mm diameter are used to investigate the dynamic tensile mechanical properties of coal sandstone for the first time. Brazilian tests at high loading rates are conducted at ambient temperature and after heat treatment at 800 °C. The effect of the strain rate on the tensile mechanical properties is analyzed using the SEM. The results show that after heat treatment at 800 °C, the dynamic indirect tensile strength of sandstone increases with the increase of strain rate. Due to the effect of thermal melting and evaporation, after treatment at 800 °C, the edges of the internal cracks in the sandstone become rough and lead to more defects. This makes the dynamic indirect tensile strength of the samples at room temperature greater than that at high temperature under the same strain rate. After heat treatment at 800 °C, as the strain rate increases, the damage morphology of sandstone changes from large arc-shaped unilateral tensile faces to small granular detrital fragments; the extent of damage gradually increases at the same time.

Key words: heat treatment, coal sandstone, tensile mechanical properties, strain rate effect, failure characteristics

Introduction

In recent years, with the improvement of the underground coal gasification technique, the utilization of geothermal resources and the development of nuclear waste storage engineering, the investigations on the mechanical characteristics of rocks after high temperature heat treatment have become a new research direction and a hot topic in the field of rock mechanics. The tensile strength of rock is much less than its compressive strength, which leads to the predominance of tensile failures when it is subjected to external loads. The loads on the rock are not static but they are dominated by dynamic loads with high strain rates [1]. Therefore, the dynamic tensile mechanical characteristics of rocks after high temperature heat treatment may have a considerable influence in the field of engineering.

The high temperatures have a significant impact on the physical properties of rock, such as its density, resistivity, and elastic wave velocity [2]. Transformation in the physical properties of rock leads to further changes in its mechanical properties. Kilic [3] demonstrated the physical properties of limestone after heat treatment. Su *et al*. [4] conducted research on the mechanical properties of grit after heat treatment between 100 °C and 900 °C and found chang-

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es in the total wave velocity, the mechanical characteristic parameters with temperature, and the mechanical properties began to change above 500 °C. Chen *et al.* [5] tested the mechanical properties of marble after heat treatment. They discussed the changes in the physical parameters and mechanical properties with temperature. Although the mechanical behavior of rocks under varied high strain rate regimes is more complex, the development of test equipment and the maturity of technology enable the research to continue. Yin *et al.* [6] used a high temperature furnace and split Hopkinson pressure bar (SHPB) test system to carry out dynamic tests on sandstone specimens at ambient temperature and thermally treated specimens at 200 °C, 400 °C, 500 °C, and 800 °C. The results showed that the dynamic compression strength of sandstone dropped swiftly as the heat treatment temperature increased. Liu *et al*. [7] did a uniaxial compression SHPB experiment on marble after high temperature heat treatment, showing that its mechanical parameters changed little below 600 °C. Above 600 °C, the peak stress and elastic modulus decreased quickly, while the peak strain increased linearly. Unlike the compression experiments, most studies on the dynamic tensile mechanical properties of rocks have been carried out at ambient temperature [8]. Although some scholars have conducted exploratory research on the dynamic tensile mechanical properties of rocks after high temperature heat treatment, they mainly focused on the damage characteristics of the specimens.

A series of experimental studies on the mechanical properties of rocks under different temperatures were carried out. However, the temperature of heat treatment is usually determined by a certain engineering process, and the load changes are mainly controlled by the strain rate. The uniaxial compression SHPB tests on sandstone after heat treatment at 800 °C was reported [9].

Test equipment and methods

Test sample collection and preparation

In this experiment, we used typical coal seam roof sandstone, taken from the – 1000 m working face of Xuzhou mine, as the rock sample. According to the test plan, rock specimens were processed into cylinders with a diameter of 50 mm and a height of 25 mm. A core-drilling machine was used to collect rock samples with the same diameter. Then a cutting machine was used to ensure that the samples are of the same height. Finally, all samples were carefully ground with a grinding machine and polished to a surface roughness of less than 0.05 mm and a surface parallelism of less than 0.02 mm. The precision of the sample processing met the qualifications of the *standard rock test method* (GB50218-94).

Test equipment

The American MTS652.02 high temperature furnace was used to heat the samples, as shown in fig. 1(a). The dynamic characterisation of the coal sandstone was done using the SHPB set-up in the State Key Laboratory of GeoMechanics and Deep Underground Engineer-

Figure 1. Test equipment and sample loading method; (a) the MTS652.02 high temperature furnace, (b) the SHPB test system, and (c) sample loading method

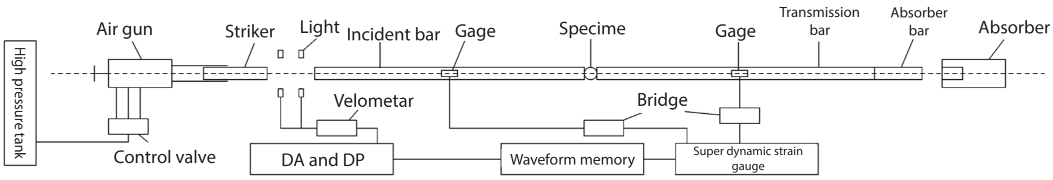

Figure 2. The SHPB test system device

ing, China University of Mining and Technology (CUMT), as shown in fig. 1(b). The SHPB test system included five parts: the loading device, incident bar, transmission bar, absorption bar and data collection and processing system. The coal sandstone specimen is sandwiched between the incident and the transmission bars, as shown in fig. 1(c). The composition of the test system is shown in fig. 2.

Table 1. The variation law of sample strain rate $\dot{\varepsilon}$ changing with pressure P

P [MPa]	Ambient temperature 800 °C			
	$\dot{\varepsilon}$ [s^{-1}]		$\dot{\varepsilon}$ [s^{-1}]	
	Discrete values	Arithmetic mean value	Discrete values	Arithmetic mean value
0.3	43.259	43.922	34.963	35.747
	45.242		36.777	
	43.264		35.501	
0.35	56.706	54.907	36.560	39.179
	54.019		39.731	
	53.996		41.247	
0.40	69.733	69.469	59.675	60.255
	70.442		61.770	
	68.231		59.320	
0.45	87.250	88.169	69.127	69.412
	87.145		70.490	
	90.113		68.619	
0.50	91.731	96.620	73.074	72.125
	99.457		71.201	
	98.672		72.100	
0.55	111.318	112.413	78.441	77.888
	108.500		77.544	
	117.421		77.678	

Experimental method

Dynamic Brazilian tests were performed on coal sandstone at ambient temperature and after heat treatment at 800 °C, these samples were then referred to as *normal sandstone* and *treated sandstone*, respectively. Treated sandstone were heated to 800 °C at a rate of 5 °C/min and held at that temperature for 1 hours, after which they were cooled to ambient temperature. Impact loads, P, were applied to the samples through the striker and the strain rate of the sandstone samples was obtained using the three-wave method. The change rule of the strain rate $\dot{\varepsilon}$ with pressure P is shown in tab. 1. This reveals that the average strain rate of the samples rose gradually with the impact pressure. Under the same impact load, the strain rate of the treated sandstone was lower than that of the normal sandstone. This is because the high temperature reduces the rate of deformation of the sandstone. Figure 3 shows the waveform schematic diagram of the SHPB experiments on sandstone after the treatment by a wave-shaping device.

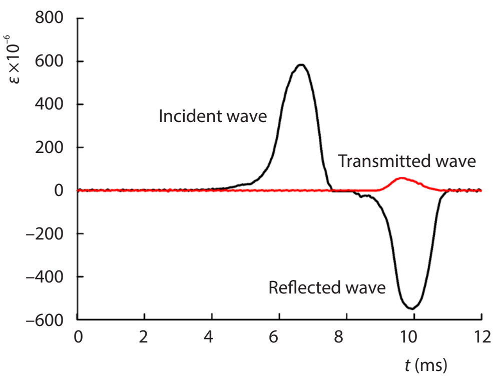

Figure 3. A typical tensile SHPB experiment waveform figure after 800 °C heat of sandstone

Results and analysis

Change rule of the dynamic tensile stress-strain curve of sandstone

The dynamic tensile stress-strain curves of normal and treated sandstone are shown in fig. 4, and the stress, ε, represents the deformation of the specimen in the loading direction. The stress-strain curves of sandstone under both conditions consist of six stages: consolidation stage, approximate linear elasticity stage, micro crack extension stage, unstable crack propagation stage, strain softening stage, and rapid unloading stage. The figures show that the strain rate has a significant effect on the dynamic tensile stress-strain curves of the rock. In the strain softening stage, the strain of treated sandstone decreased with the increase of strain rate, while the strain of normal sandstone remained approximately unchanged. The mechanical characteristic parameters changed prominently with the strain rate. Under two temperature conditions, the dynamic tensile modulus and dynamic tensile strength increased as the strain rate increased. The peak dynamic tensile strain of the treated sandstone gradually increased as the strain rate increased. In contrast, the tensile failure strain gradually decreased as the strain rate increased for the normal sandstone.

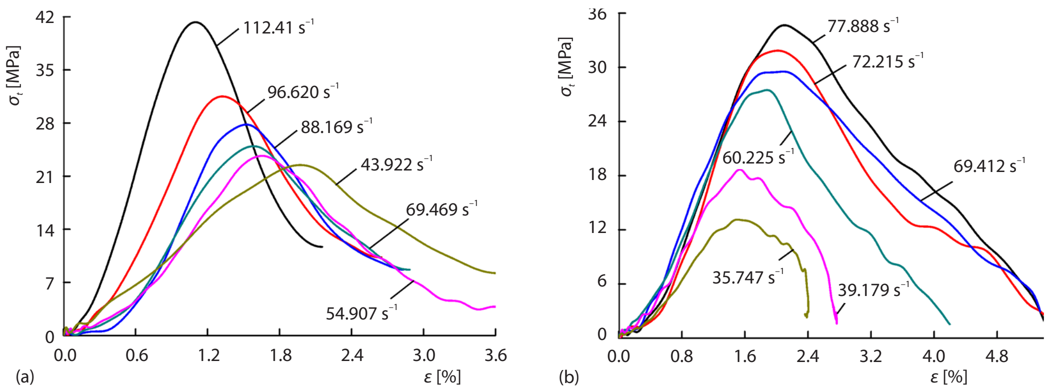

Figure 4. Dynamic tensile stress-strain curve of sandstone; (a) under the ambient temperature, (b) 800 °C heat treatment

Change rule of the dynamic tensile characteristic parameters of sandstone

According to the dynamic tensile stress-strain curves of sandstone, fig. 5 shows the variation between dynamic tensile peak stress σ_t and the strain rate under two temperatures.

Dynamic peak tensile stress is also known as dynamic tensile strength, which is the embodiment of the ultimate bearing capacity of sandstone under a high strain rate. From fig. 4, we found the variation curve of the dynamic peak tensile stress of sandstone, σ_t, along with the strain rate, $\dot{\varepsilon}$, at ambient temperature and after heat treatment at 800 °C. We can see from the graph that the dynamic peak tensile stress increased gradually with the increase of strain rate under both temperature conditions, and changed in the form of a quadratic function. However, there was a difference in the change process of the fitting function under two temperature conditions. The results show that the peak tensile stress of treated sandstone is higher than that of normal sandstone in the same strain rate range. The relationship between the dynamic peak tensile stress and strain rate of coal sandstone under two temperature conditions can be written:

$$\sigma_t = \begin{cases} 0.0028\dot{\varepsilon} + 0.7269\dot{\varepsilon} - 7.293 \quad R^2 = 0.9120 \quad T = 25\,^\circ\mathrm{C} \ \text{(normal. temp.)} \\ 0.0038\dot{\varepsilon} - 0.3260\dot{\varepsilon} + 28.70 \quad R^2 = 0.8761 \quad T = 800^\circ\mathrm{C} \end{cases} \tag{1}$$

where σ_t is the dynamic peak tensile stress of sandstone, $\dot{\varepsilon}$ – the loading strain rate, T – the heat treatment temperature, and R^2 – the coefficient of determination.

Under the impact load, after the unstable expansion stage of deformation, a large number of cracks, holes, and other internal defects were formed in the sandstone and its carrying capacity was mainly due to the friction between particles. A SEM was used to observe the fracture morphology of the sandstone, as shown in fig. 6. The sandstone fracture surface was relatively flat at ambient temperature, and had a few tiny cracks, fig. 6(a). Both sides of the crack were relatively smooth, fig. 6(b) and the friction between particles on both sides of the crack was relatively small under the impact load. After the heat treatment at 800 °C, a lot of hot melt holes and mutual-linked cracks were present on the sandstone fracture surface, fig. 6(c), and both sides of the crack surface were obviously indented, fig. 6(d). Under the impact load, crack extension needed to overcome more friction. In addition, the high temperature treatment evaporated the water in the sandstone, which was why the peak dynamic tensile stress at 800 °C was greater than that at ambient temperature.

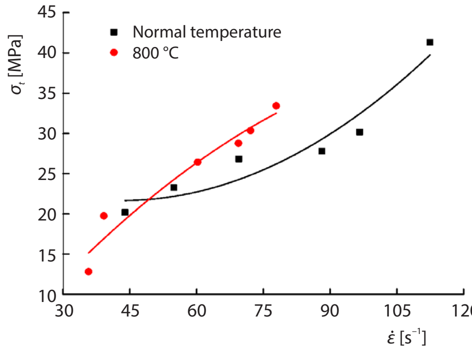

Figure 5. Variation curve of dynamic tensile peak stress with strain rate

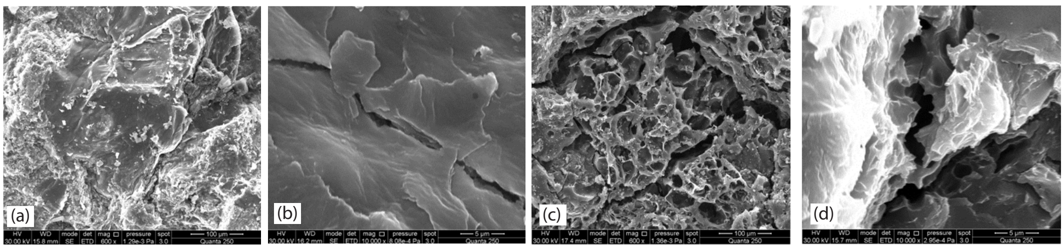

Figure 6. The SEM image of sandstone of fracture morphology; (a) and (b) at ambient temperature, (c) and (d) at the 800 °C after heat treatment

After heat treatment at 800 °C, the strain rate increased from 35.747-77.888 s^{-1}, and the dynamic tensile stress of sandstone increased by approximately 1.61 times. The specific change characteristics manifested as:

– the strain rate increased from 35.747-39.179 s^{-1}, and the peak dynamic tensile stress of sandstone increased rapidly from 12.82 to 19.75 MPa, with an amplitude of 54.06%,
– the strain rate increased from 39.179-77.888 s^{-1}, and
– the peak dynamic tensile stress of sandstone increased from 19.75-33.42 MPa, with an amplitude of 69.21%, showing an approximately linear increase, but the change rate decreased.

Change rule of the dynamic tensile failure characteristics of sandstone

Figure 7 shows the splitting tensile failure pattern of the treated sandstone under different strain rates. It can be seen from the diagram that under different strain rates the samples were destroyed; however, there were significant differences in the form of the fragments and the extent of damage to the specimens.

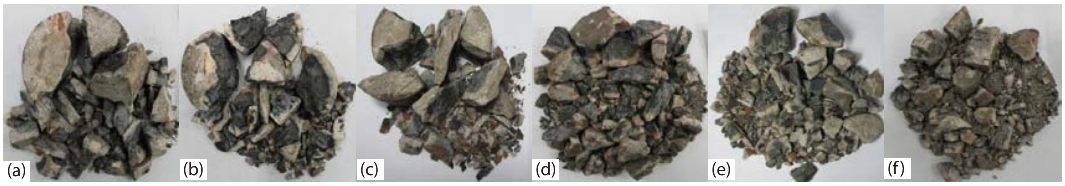

Figure 7. The tensile failure of sandstone specimens under different strain rate; (a) $\dot{\varepsilon}$ = 35.747 s^{-1}, (b) $\dot{\varepsilon}$ = 39.179 s^{-1}, (c) $\dot{\varepsilon}$ = 60.255 s^{-1}, (d) $\dot{\varepsilon}$ = 69.412 s^{-1}, (e) $\dot{\varepsilon}$ = 72.125 s^{-1}, and (f) $\dot{\varepsilon}$ = 77.888 s^{-1}

Through statistical analysis of the morphology of the fragments with the vertical height less than 2 cm after destruction of the samples. Under low strain rate ($\dot{\varepsilon}$ = 35.747 s^{-1}, $\dot{\varepsilon}$ = 39.179 s^{-1}), there were large-volume, arc shape sections of debris that had unilateral tension faces after the samples were damaged. At the same time, there were also a certain number of bilateral fan-shaped sections of debris with a tension face, and some granular detrital fragments. As the strain rate ($\dot{\varepsilon}$ = 60.255 s^{-1}) increased, the majority of the fragments had bilateral tension face fan-shaped sections. There was a small number of bilateral tension face rectangular section fragments, and the granular detrital increased. When the strain rate increased further ($\dot{\varepsilon}$ = 69.412 s^{-1}, $\dot{\varepsilon}$ = 72.125 s^{-1}, and $\dot{\varepsilon}$ = 77.888 s^{-1}), the number of large-volume fragments decreased, and the fragments were mainly in the form of small granular detrital. There were some pieces with bilateral tension face fan-shaped sections and parts of small fragments with tension face rectangular sections on both sides.

Conclusion

In our work, we inspected the dynamic mechanical properties of sandstone after high temperature heat treatment and explained the mechanical behavior of the strain rate effect from the composition characteristics and mesoscopic structure point of view. The dynamic tensile stress-strain curves of sandstone at ambient temperature and 800 °C were divided into six stages: consolidation stage, approximate linear elasticity stage, micro crack extension stage, unstable crack propagation stage, strain softening stage, and rapid unloading stage. After heat treatment at 800 °C, the strain rate increased from 35.747-77.888 s^{-1}. The dynamic peak tensile stress of sandstone increased gradually by 1.61 times. The results of scanning electron microscopy showed a large number of hot melt holes and intersecting cracks on the fractured surface of the sandstone after heat treatment at 800 °C. Furthermore, both sides of the cracks were rougher, and the difference in the microstructure resulted in greater peak stress after heat treatment than the corresponding value of sandstone under ambient temperature within the same strain rate range. After heat treatment at 800 °C, the debris of the damaged sandstone sample changed from mainly large-volume, arc shape cross-section pieces with unilateral tensile faces to larger-volume, fan-shaped section debris with bilateral tensile faces, and finally to small granular detrital fragments.

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