EXPERIMENTAL RESEARCH OF LOADING RATE EFFECT ON BRITTLE-DUCTILE TRANSITION OF MUDSTONE UNDER HIGH TEMPERATURE

by

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To investigate the brittle ductile transformation characteristics of mudstone under high temperature, the MTS810 electro mechanical hydraulic servo test system and matched high temperature furnace MTS652.02 are used to perform mechanical tests to study the influence of loading rate on the yield strain and ductility coefficient of the mudstone at high temperatures.

Key words: *mudstone at high temperature, loading rate, yield strain, ductility coefficient, brittle-ductile transition*

Introduction

The loading rate is a parameter that varies over a large span. In general rock engineering, the unloading rate of blasting mining, for example, is a fraction of a second, while in the field of underground mining roadway and pillar, the increment of deformation is only 0.10~0.15 mm per year. With different loading rates, the mechanics and deformation properties of rock material illustrate significantly different performance. Therefore, the mechanics performance of rock material under different loading rate effect has always been regarded as the focus of researches on the rocks' rheological properties. Brittle-ductile transformation is a special deformation property of rocks, which involves corresponding changes of mechanical behavior, macro structure and micro mechanism. Studying brittle-ductile transformation of rock has significant influence on the understanding the solid flow of deep underground rock, analysis of ultimate bearing capacity of overburden rock and many other aspects [1-4].

Many scholars did a lot of researches on the brittle-ductile transformation of the rock and found that the dominant factor of brittle-ductile transformation was temperature [5-7]. But in recent years, it has been shown that the strain rate also had significant impacts on the control of brittle-ductile transformation [8-16]. Wang [8] through deformation test, pointed out that along with changes of factors including mineral composition, particle size, temperature, confining pressure, strain rate, liquid medium and*, etc.*, rocks would be transformed from being brittle to half brittle, half ductile and ductile in turn, including mechanical behavior changes of microscopic mechanism and macroscopic structure. In addition, Brede [9] studied the effect of temperature on the brittle-ductile transition of materials and found that the temperature at which the brittle-ductile transition occurred increased with the displacement loading rate. Sang [10] focused on the test of the brittle-plastic transformation of gabbro, and concluded that the main influencing factors were temperature, confining pressure and strain rate. Renard [11] and

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other research results [12-14] relied on field test, experiment in lab and seismic data which pointed out that past researches on brittle-plastic conversion belt of fault mainly concentrated on the transformation that was caused by temperature. However, there were limited researches on the influence that strain rate and fluid had on brittle-plastic transformation. The study on the mechanism of mineral deformation within the fault zone showed that certain brittle-plastic transformation of the fault belt occurred at the same depth (temperature and pressure), and the change of strain rate was the reason why brittle plastic varied.

With regard to rock mechanics, the researches on rock brittle-ductile transformation focused on temperature or loading rate effect only, while few studies on the combing effects of both simultaneously, which was the theoretical basis of blasting mechanism, rock failure criterion, rock engineering parameter optimization and*, etc.* Therefore, through the MTS810 electro mechanical hydraulic servo testing machine, the uniaxial compression tests of the mudstone under high temperature were conducted. The loads were exerted according to the displacement control, in which displacement loading rate was divided into 4 levels ranging from $3 \cdot 10^{-3}$ mm/s to 3 mm/s. Through the analysis of entire stress-strain process curves, this paper discusses the influence of loading rate on the brittle-ductile transformation and damage evolution mechanism of mudstones under high temperature.

Figure 1. Matching of MTS810 and MTS652.02

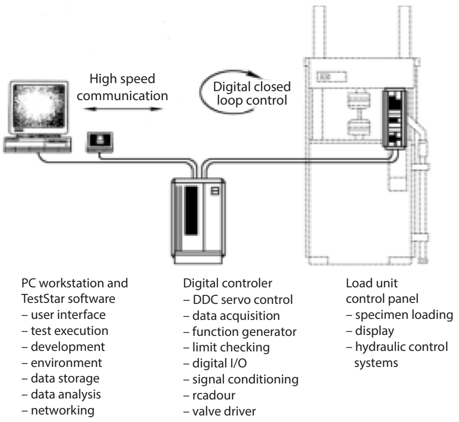

Figure 2. Composition of MTS810 system

Experiments

The tests were performed with MTS810 electro mechanical hydraulic servo test system and the matched high temperature furnace MTS652.02, shown in fig. 1. There were 20 groups in total and each group had 3 pieces of specimens, which were made and heated with a rate of 2 °C/s up straight to 25 °C, 200 °C, 400 °C, 600 °C, and 800 °C, respectively. The temperature of each group was maintained at a constant level for 20 minutes in the furnace MTS652.02 after being heated, to ensure the specimens were heated evenly. Under the uniform temperature, the rock specimens were loaded with the displacement control method of electro-hydraulic servo material test system with different displacement loading rates of 0.003 mm/s, 0.03mm/s, 0.3 mm/s, and 3 mm/s, respectively, until the specimens were damaged. The whole process was completed by the systematically matched TeststarIIsystem, shown in figs. 2 and 3, following preset requirements. The system conducted the optimized control of the testing process through computers. It could allocate sensor, define control mode, set boundaries, make sensitive element zero automatically, select output signal and set some parameters when necessary through the main form of the menu. The system software included a graphical user interface, data interface, software function generator, program design and system tools. The values of related physical quantities, axial load, axial displacement, axial stress and strain, and so on were recorded simultaneously in the process of the experiment.

Results and discussions

The ductility coefficient of the rock, denoted as η, is defined:

$$\eta = \frac{\varepsilon_c}{\varepsilon_s} \tag{1}$$

where ε_c is the peak strain, obtained through entire stress-strain process curve based on mudstone uniaxial compression test at different loading rates, and ε_s – the yield strain, calculated by the corresponding strain of 80% peak stress. For completely brittle materials, ductility coefficient could be 1.25 [17].

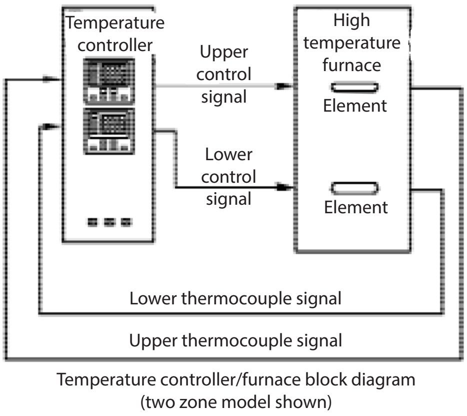

Figure 3. Composition of furnace MTS652.02

The peak stress and peak strain were obtained from the whole stress-strain process curve based on mudstone uniaxial compression test under different loading rates in [17]. Figures 4-8 show the variation of yield strain, ε_s, and ductility coefficient, η, of the mudstone with the loading rate, v, under different temperatures.

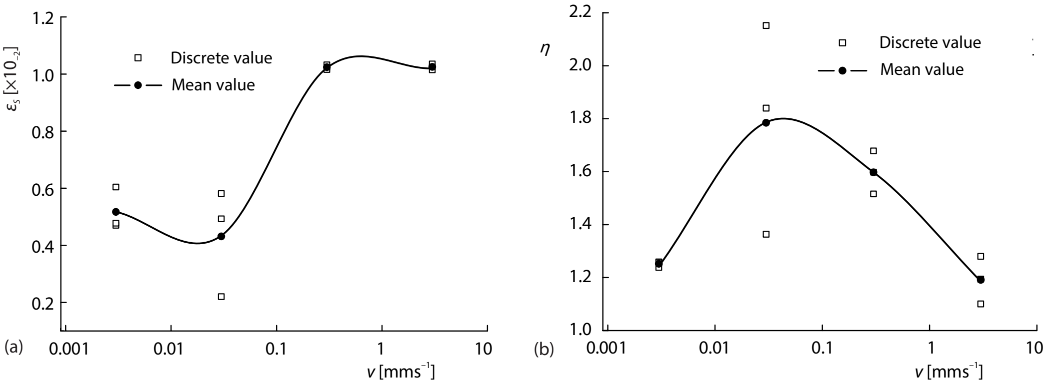

Figure 4. Change curves of yield strain, ε_s, and ductility factor, η, with loading rates at room temperature

From fig. 4, it is found that: with an increase in loading rate, the yield strain of mudstone rises gradually; as the loading rate rising up from 0.03 mm/s to 0.3 mm/s, the yield strain of mudstone increases greatly by approximately 68.33% and as the loading rate increasing from 0.003-0.03 mm/s, the ductility coefficient of mudstone increases from 1.252-1.2520. The breaks of mudstone show some certain ductility features, and an increase in loading rate improves the ductility of mudstone samples to some extent. When the loading rate rises to 3 mm/s, the ductility coefficient drops to 1.1916 rapidly, reflecting the brittle failure characteristics of the mudstone specimens.

Figure 5 shows changes of yield strain, ε_s, and ductility coefficient, η, with the loading rate of the mudstone at 200 °C. It could be seen that: the yield strain of mudstone generally is increasing gradually with the loading rate, which is similar to that at room temperature; when the loading rate is between 0.003 mm/s and 0.03 mm/s, the yield strain of the mudstone increases greatly and the increase of mudstones' ductility coefficient with loading rate is not obvious, without demonstrating clear loading rate effects.

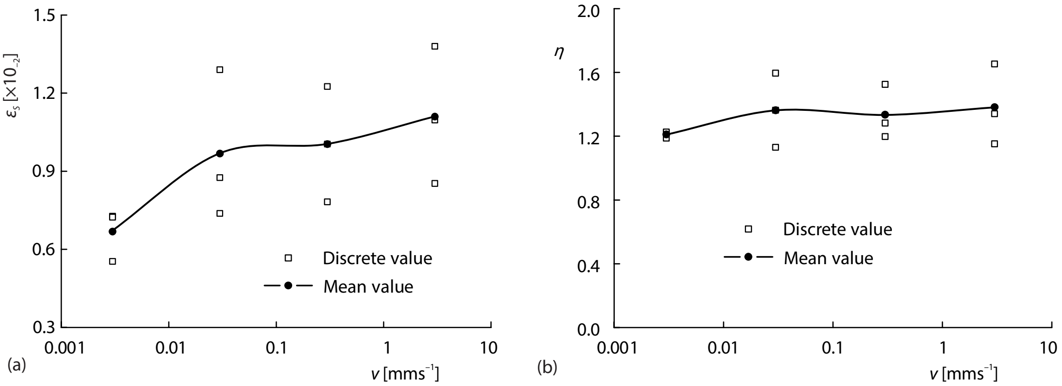

Figure 5. Change curves of yield strain, ε_s, and ductility factor, η, with loading rates at 200 °C

It could be seen from fig. 6 that the change laws of yield strain ε_s and ductility coefficient η with loading rate at 400 °C are obvious different from that at room temperature: with the loading rate increasing, the yield strain of mudstone significantly fluctuates with the loading rate; when the loading rate increases from 0.003-0.03 mm/s, the yield strain of the mudstone decreases by about 51.52%, from $0.8573 \cdot 10^{-2}$ to $0.4156 \cdot 10^{-2}$. When the loading rate raises from 0.03-0.3 mm/s, the yield strain of the mudstone increases to $0.6433 \cdot 10^{-2}$, rising by about 54.79%; while, the yield strain of mudstone declines by about 44.27% with loading rate continues increasing up to 3 mm/s and when the loading rate increases from 0.003-0.03 mm/s, the ductility coefficient of the mudstone raises from 1.2782-1.4892 and rock damages start to demonstrate certain brittle failure features. When the loading rate increases from 0.03-0.3 mm/s, the ductility coefficient of the mudstone drops to 1.2173, indicating brittle failure. After the loading rate being added up to 3 mm/s continuously, the ductility factor of the mudstone rises to 1.5807. As the loading rate increased from 0.003-3 mm/s, the ductility coefficient fluctuates in the vicinity of $\eta = 1.25$, and the change is not obvious reflecting the characteristics of brittle failure.

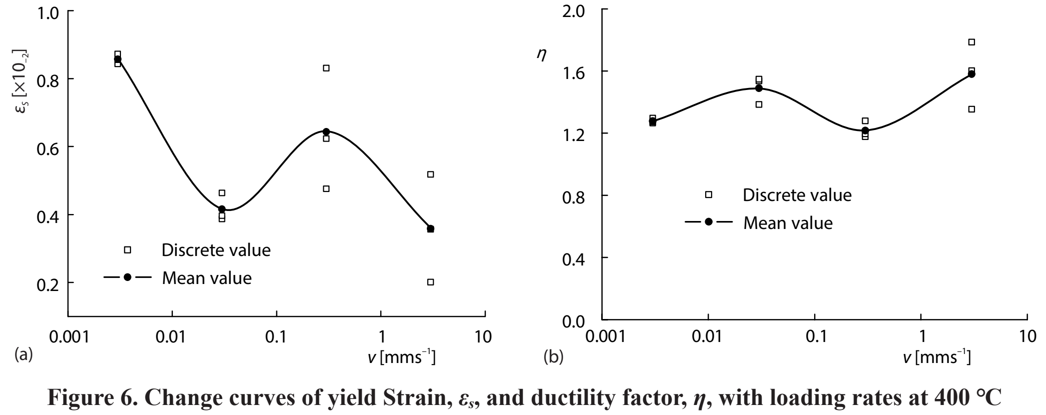

Figure 6. Change curves of yield Strain, ε_s, and ductility factor, η, with loading rates at 400 °C

The way that the yield strain ε_s and ductility coefficient η vary with the loading rate of mudstone under 600 °C is shown in fig. 7. With the increase in loading rate, the changing rule of the yield strain of the mudstone is opposite to that at 400 °C. When the loading rate increases from 0.003-0.03 mm/s, the yield strain of the mudstone raises by about 50.83% from $0.5296 \cdot 10^{-2}$ to $0.7964 \cdot 10^{-2}$. As the loading rate increases from 0.03 mm/s to 0.3 mm/s, the yield strain of the mudstone decreases by about 47.79% to $0.4158 \cdot 10^{-2}$. When the loading rate continues to go up to 3 mm/s, the yield strain of the mudstone climbs to $0.5490 \cdot 10^{-2}$. The ductility coefficient of the mudstone firstly decreases and then increases as the loading rate goes up. When the loading rate increases from 0.003-0.03 mm/s, the ductility coefficient of the mudstone decreases from 1.5059-1.2171, during which the increase of the loading rate weakens the ductility characteristics of the mudstone. When the loading rate increases from 0.03-3 mm/s, the ductility factor of the mudstone rises to 2.0049, illustrating obvious characteristic of ductility damage.

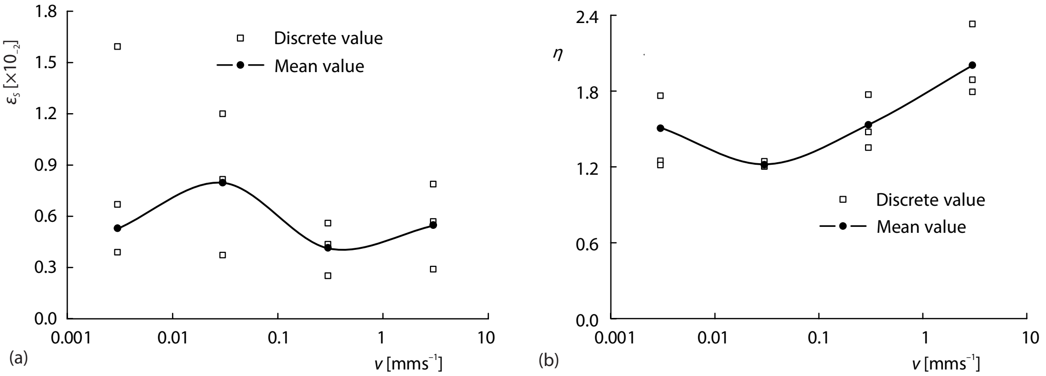

Figure 7. Change curves of yield strain, ε_s, and ductility factor, η, with loading rates at 600 °C

How the yield strain ε_s and ductility coefficient η of mudstone at 800 °C changes with the loading rate is shown in fig. 8. It can be seen that: when the loading rate increases, the yield strain of mudstone undulates significantly with a tendency of going up firstly and then falling down; as the loading rate increases from 0.003-0.03 mm/s, the yield strain of the mudstone rises totally by about 165.70% from $0.5140 \cdot 10^{-2}$ to $1.3657 \cdot 10^{-2}$; when the loading rate increases from 0.03 mm/s to 0.3 mm/s, the yield strain of the mudstone decreases 44.19% to $0.7622 \cdot 10^{-2}$. The yield strain of the mudstone reaches $0.4248 \cdot 10^{-2}$ when the loading rate rises up to 3 mm/s

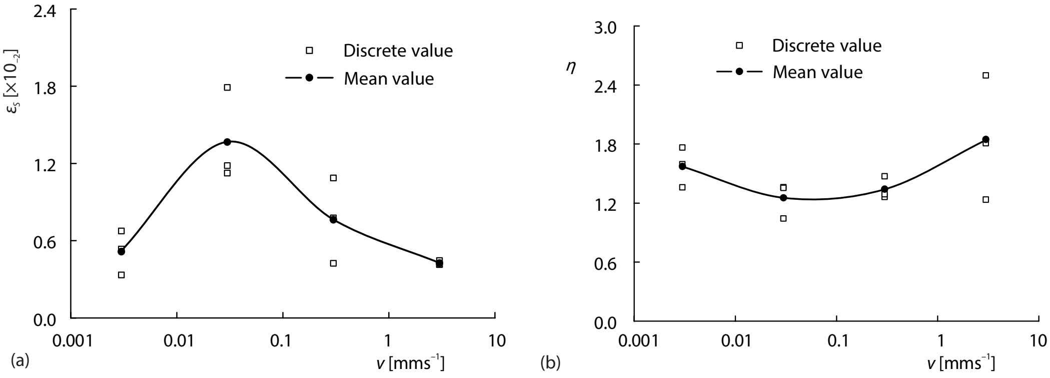

Figure 8. Change curves of yield Strain, ε_s, and ductility factor, η, with loading rates at 800 °C

and the ductility coefficient of the mudstone decreases and then rises up as the loading rate increasing. When the loading rate increases from 0.003-0.03 mm/s, the ductility coefficient of the mudstone decreases from 1.5734-1.2529, and the process of the loading rate increasing weakens the ductility characteristics of the mudstone. When the loading rate increases from 0.03-3 mm/s, the ductility coefficient of the mudstone rises up to 1.8472, indicating obvious features of ductility damage.

Conclusion

The mudstone have presented the typical brittle failure at room temperature and low loading rate, and its failure mode changes as the loading rate increasing. With the growth of loading rate, the yield strain of mudstone gradually increases as a whole. Based on the ductility coefficient, with the raising of loading rate, its failure form illustrates brittle-ductility-brittle transition law. Under the temperature condition of 200～400 ℃, the mudstone appears volume expansion due to heat, the original crack opening scale decreases or even closes, and combination between mineral grains becomes tighter. As the loading rate increases, the characteristics of brittle-ductility transformation of mudstone samples are not obvious and show typical brittle failure.

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Nomenclature

ε_s – yield strain, [–]
ε_c – peak strain, [–]
η – ductility coefficient of the rock, [–]

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