EFFECT OF THERMAL CYCLING ON MECHANICAL PROPERTIES AND ENERGY EVOLUTION OF SANDSTONE

by

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Original scientific paper
https://doi.org/10.2298/TSCI2006001H

In geothermal energy exploration, the reservoir rock is always subjected to thermal cycles and its physical properties will be seriously affected. In this paper, the changes of the internal structure of the sandstone after the thermal cycle are firstly evaluated by ultrasonic tests. Then, uniaxial compression tests are conducted on the treated specimens. The effects of the thermal cycling on mechanical properties and energy evolution law of the sandstone are analyzed. The results show that the density, P-wave velocity and mechanical properties of the sandstone reduced with the increase in the thermal cycle, especially in the high temperature cycle. The increase of the temperature in the thermal cycle can increase the influence of the thermal cycle on the energy evolution law.

Key words: *geothermal energy, sandstone, thermal cycling, energy evolution, mechanical properties*

Introduction

The geothermal energy, as a renewable, clean and abundant energy resource, has become a hot study area due to the urgency of conventional energy sources [1]. In geothermal energy exploration, a heat-exchange process usually is employed to capture and extract thermal energy by the injection of cool water [2]. During this process, the reservoir rock is always subjected to thermal cycles, and the physical properties of reservoir rocks will be seriously affected due to the significant changes in the internal structure [3]. Therefore, to improve the overall efficiency and flexibility of the geothermal energy development, it is necessary to understand the mechanical behaviors of reservoir rocks subjected to the thermal cycle.

So far, there have been some efforts to explore the changes in the mechanical properties of rocks under thermal cycles. Mahmutoglu [4] studied the mechanical behaviors of the Carrara marble and Buchberger sandstone under the thermal cycles, and their strength properties are significantly weakened after the thermal cycling. Zhu *et al.* [5] also exper-

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imentally studied the effects of temperature cycling on the compressive strength, residual strength and elastic modulus of marble under uniaxial compression. Xu and Sun [6] studied the changes in the tensile strength of the granite with the thermal cycle and the results indicate that there is a negative relationship between the tensile strength and the thermal cycle number. Liu *et al.* [7] investigated the mechanical properties of the sandstone under the low temperature cycling treatment. Sun *et al.* [8] studied the effects of the temperature cycles on the mechanical properties of the sandstone by the uniaxial compression tests and Brazilian splitting tests. They found that the peak strength and tensile strength of the sandstone reduce and its plastic characteristic increases. From the literature review, the current researches mainly focus on the traditional mechanics analysis. The deformation and failure process of rock present complexity, fuzziness and uncertainty due to the heterogeneity and discontinuous microstructure of rock [9, 10]. The nature of rock failure is a process of the energy accumulation, energy dissipation, and energy release [11]. Therefore, the study on the energy evolution of the rock failure process can enrich and deepen the people's cognition of the rock mechanical behaviors, which contributes to solving the relevant practical engineering problems accurately.

The main aims of the paper are to show that the sandstone samples are treated by the different thermal cycles, and that the ultrasonic tests and uniaxial compression tests are conducted on the treated specimens, successively. The elastic energy density and dissipated energy density of the sandstone during the failure process are calculated. The effects of thermal cycling on mechanical properties and energy evolution of the sandstone are analyzed.

Experimental process and energy calculation method

Sample preparation

Sandstone samples were taken from Xuzhou, Jiangsu, China and their pore structures are relatively homogeneous. The main minerals of the sandstone are quartz, feldspar, and calcite. All specimens were drilled from the same block to guarantee the reliability of experimental results and the sandstone samples were processed into cylinders with 100 mm in length and 50 mm in diameter. A total of 51 samples were prepared and the processed samples are shown in fig. 1(a).

Figure 1. Sandstone samples and experimental equipments; (a) sandstone samples, (b) high temperature heating chamber, (c) NM-4A non-metal ultrasound detector, and (d) MTS-816

Thermal cycle process

The heating apparatus is a high temperature heating chamber with an automatic control function and is shown in fig. 1(b). To reflect the real environmental conditions of deep rocks, the four temperatures (200, 400, 600, 800 °C) are designed. The heating rate of 5 °C per minute is set. The specimens are kept at the target temperature for two hours to ensure the uniform heating of the samples. After that, the specimens are taken out to cool down naturally to room temperature for three hours. Those two steps are regarded as one thermal cycle. The heating-cooling process is repeated and four cycle types (1, 5, 10, 15 cycles) are performed. To accurately obtain the experimental results, three specimens are used at each designed thermal cycle. In addition, the density and *P*-wave velocity of the samples are measured before and after the thermal cycling. The NM-4A non-metal ultrasound detector is applied to measure the *P*-wave velocity and it is shown in fig. 1(c).

Uniaxial compression test process

The uniaxial compression tests are performed on the MTS-816 electro-hydraulic servo-controlled rock mechanic testing system with an axial load capacity of 1459 kN. The strain and axial load data can be automatically recorded and stored in the computer. During the tests, the loading rate is controlled at the 0.05 mm per minute by the displacement.

Energy calculation method

The deformation and failure of rock are closely related to its internal energy conversion. Supposing that the whole physical process is a closed system and there is no heat exchange with the external environment, the law of energy conservation for rock failure process can be expressed [12]:

$$u = u^e + u^d \tag{1}$$

where u is the total absorbed energy, u^e – the elastic energy, and u^d – the dissipation energy.

A typical stress-strain curve of rock under the uniaxial compression test is shown as fig. 2. Based on the thermodynamics, the dissipated energy is irreversible, while the elastic energy is reversible [10]. From fig. 2, the total absorbed energy u and elastic energy density u^e can be calculated [12]:

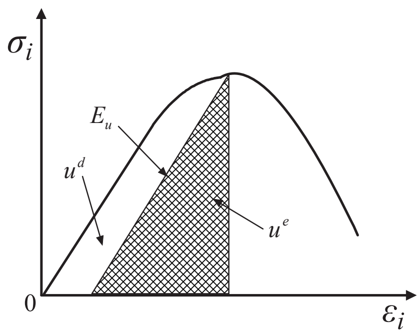

Figure 2. Calculation diagram of elastic energy and dissipation energy

$$u = \int_0^{\varepsilon_i} \sigma \,\mathrm{d}\varepsilon \tag{2}$$

$$u^e = \frac{1}{2}\sigma_i \varepsilon_i^e = \frac{1}{2}\frac{\sigma_i^2}{E_u} \tag{3}$$

where E_u is the elastic modulus, ε – the strain, ε^e – the elastic strain, σ – the stress, and i – the stress state.

Results

Physical properties

The density and *P*-wave velocity of the sandstone after and before the thermal cycle are shown in fig. 3. The density decreases with the increasing of the temperature and the lower density can be found at the high thermal cycle. At the low temperature cycle, the free water in the pores is evaporated, while the bound water in the particles will be further removed and the mineral particles are pyrolyzed with the increase in the temperature. Therefore, the density of the sandstone varies with the temperature and thermal cycle number. The *P*-wave velocity of the sandstone has a decrease with the increasing of the tem-

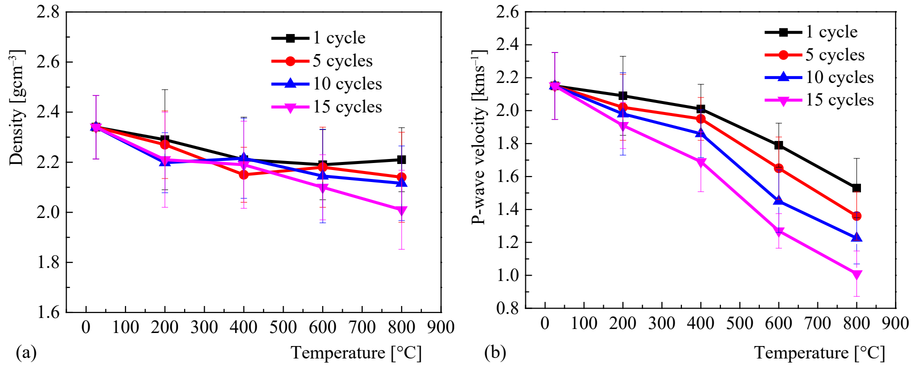

Figure 3. Variations in density and *P*-wave velocity of sandstone after thermal cycles; (a) density and (b) P-wave velocity

perature and thermal cycle, and its variation trend with respect to the temperature is affected by the thermal cycle number. The *P*-wave velocity of the sandstone decreases in two steps with the increase in the temperature when the thermal cycle is less than 10. The decreased *P*-wave velocity of the sandstone is not remarkable in the temperature range of 25-400 °C, while it reduces rapidly when the temperature is in the range of 400-800 °C. At the 15 thermal cycles, the above phenomenon vanishes and the P-wave velocity of the sandstone decreases sharply from the temperature 25 °C to 800 °C, indicating a quick degradation of the sandstone structure. At the high temperature cycle, the damage of the crystal structure is easily induced and the internal defects increase due to the loss of water, pyrolysis of mineral particles and large thermal stress.

Mechanical properties

The stress-strain curves of the treated sandstone samples are displayed in fig. 4. In the temperature range of 200-400 °C, the effect of the thermal cycle on the stress-strain curve is not significant. However, the stress-strain curve moves toward right with the increase in the thermal cycle when the temperature is larger than 400 °C. Base on the stress-strain curves, the compressive strength, elastic modulus and strains at the peak strength of specimens are plotted in fig. 5.

The compressive strength decreases with the increasing of the temperature and the decrease degree is enhanced with the rising of the thermal cycle. At the same time, it can be seen that the decrease rate of the compressive strength in the temperature range of 400-800 °C is obviously larger than that in the temperature range of 25-400 °C. The results indicate that the low temperature has little effect on the structure and mineral composition of the sandstone even if the number of thermal cycles increases. At the high temperature range, the internal structure and mineral composition of the sandstone are greatly affected and this influence raises with the increase in the thermal cycle. The elastic modulus and strain at the peak strength reduces and increases with the increasing of the temperature, respectively. Similar to the compressive strength, the effect of the thermal cycle on the elastic modulus and strain at the peak strength of specimens at the low temperature is small, while the influence increases gradually with the rising of the temperature. Generally, the stiffer the rock is, the higher the compressive strength and the stronger the anti-deformation ability are. Therefore, after the high temperature and large thermal cycles, the mechanical properties of the sandstone are remarkably weakened and its ability to resist deformation is reduced.

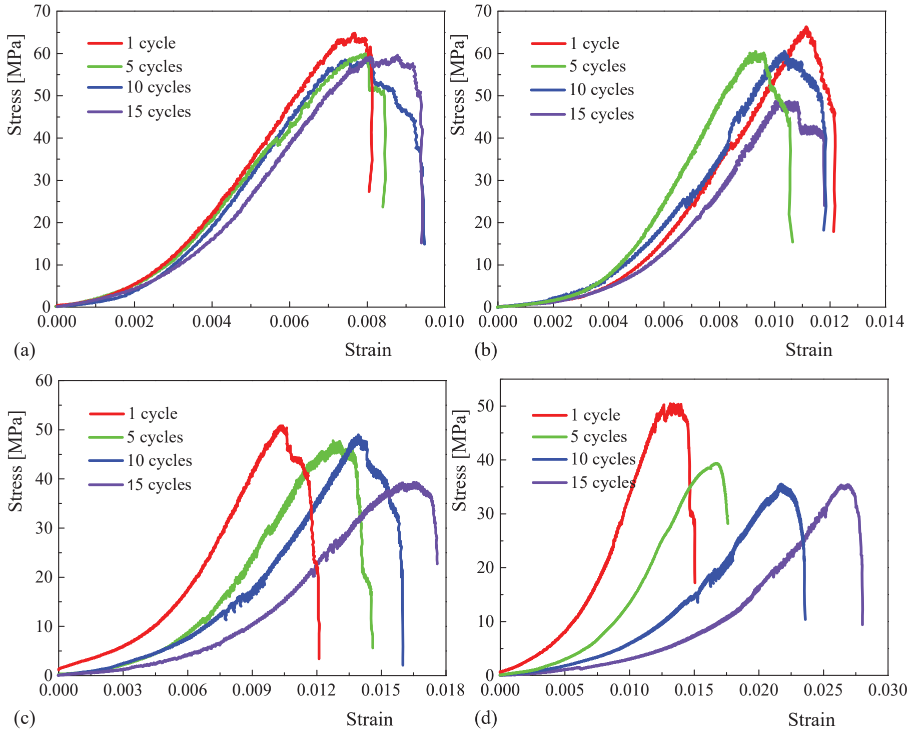

Figure 4. Stress-strain curves; (a) 200 °C, (b) 400 °C, (c) 600 °C, and (d) 800 °C

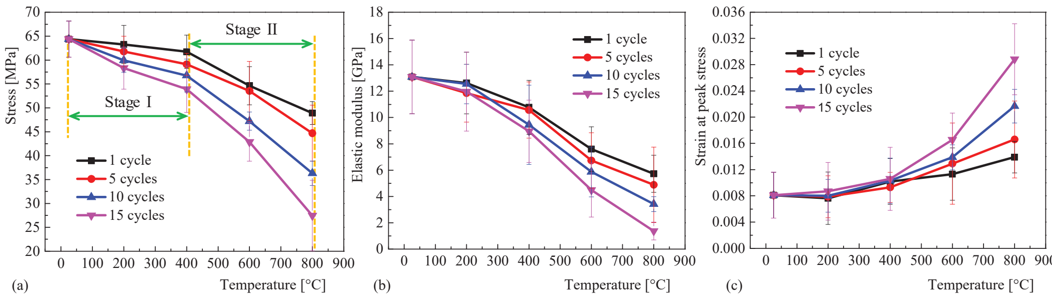

Figure 5. Changes in mechanics parameters after thermal cycle; (a) compressive strength, (b) elastic modulus, and (c) strain at peak stress

Energy evolution law

The elastic energy density and dissipated energy density of the sandstone during the deformation and failure process are calculated and shown in fig. 6. The elastic energy density of the sandstone presents a non-linear growth with the increase in the axial stress. The elastic energy density increases slowly at the stages of compaction and elasticity, while it increases sharply at the plastic stage. The elastic energy density has an increasing trend with the increasing of the thermal cycle, it becomes more significant with the increase in the temperature of the thermal cycle. At the low temperature or low cycles, the dissipated energy density slowly rises before the failure and increases sharply near the failure. With the increasing of temperature

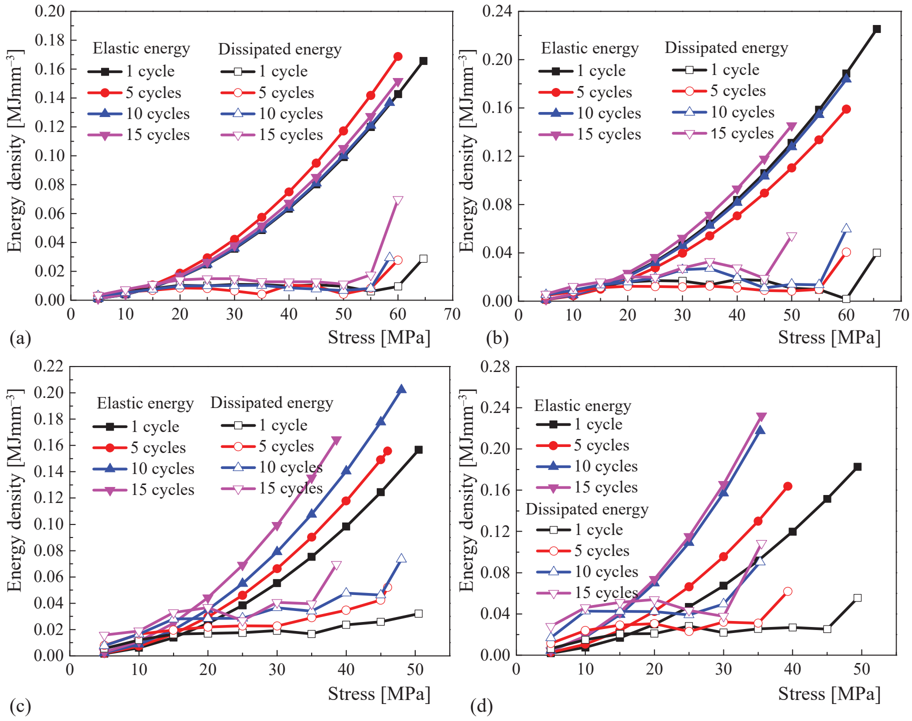

Figure 6. Energy density – axial stress curves; (a) 200 °C, (b) 400 °C, (c) 600 °C, and (d) 800 °C

and thermal cycle, the dissipated energy density has a peak before the failure and it's growing faster, especially at the failure.

Under the same stress level, the more the internal defects are, the smaller elastic modulus and the greater the deformation are, which can significantly result in the increasing of the elastic energy density based on eq. (3). The slip and friction become more active due to a large number of internal defects. As a result, the dissipated energy increases during the deformation and failure process, especially near the failure. Thus, the high temperature and high thermal cycles have a considerable influence on the energy accumulation and dissipation of the sandstone owing to the significant changes in the mineral composition and internal structure of the sandstone.

Proportion evolutions of elastic energy density and dissipated energy density in total absorbed energy density are presented in fig. 7. The energy distribution laws of the sandstone under different thermal cycles are similar to an extreme extent. The proportion of elastic energy density increases gradually before the failure of the sandstone samples and then begins to reduce rapidly near the peak stress. However, there is just an opposite change in the proportion of dissipated energy density. It can be seen that the proportion of dissipated energy density is more than that of the elastic energy density at the compaction stage due to a large amount of heat induced by the friction of the matrix particles and friction slippage of the micro-cracks. In the thermal cycle, the proportion of elastic energy density obviously decreases with the increase in the temperature. The maximums proportion of elastic energy density is very close to 1.0 when the temperature is less than 400 °C, while its value is about 0.8 in the temperature range of 400-800 °C. The stiffer the rock is, the higher the potential of energy accumulation at

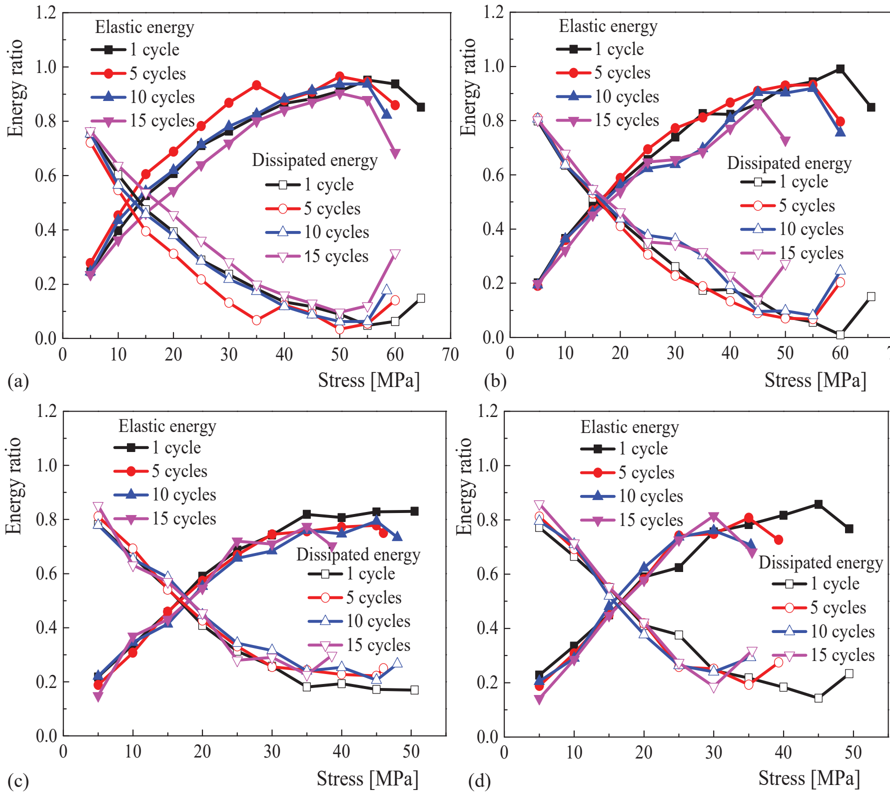

Figure 7. Proportion evolution of elastic energy and dissipated energy in total absorbed energy; (a) 200 °C, (b) 400 °C, (c) 600 °C, and (d) 800 °C

the pre-peak stage is [10]. The results indicate that sandstone stiffness decreases with the rising of the temperature. On the verge of the sample failure, the proportion of elastic energy density reduces slowly when the temperature is larger than 400 °C, while it decreases rapidly at less than 400 °C. The proportion of dissipated energy density keeps a relatively large value in the thermal cycle with a high temperature, while it has a sharp increase when the temperature of the thermal cycle is larger than 400 °C. In the thermal cycle with the low temperature, the accumulated elastic energy in the sandstone is released instantly and is transferred into the dissipated energy, causing a rapid increase in the dissipated energy. In the thermal cycle with the high temperature, many microfractures are induced in sandstone specimens and the accumulated elastic energy is slowly released, resulting in the relatively high proportion of dissipated energy. With the increase in the thermal cycle, the proportion of elastic energy density has a decreasing trend and the proportion of dissipated energy density slightly increases.

Discussion

According to the aforementioned results, the thermal cycle has a significant influence on the physical properties, mechanical properties, and energy evolution law of the sandstone and this effect is different under different temperatures. By the temperature treatment, various physical changes inside the sandstone are induced as shown in figs. 8(a) and 8(b). In the thermal cycle with the low temperature, the inter-particles cracks are generated by water evaporation.

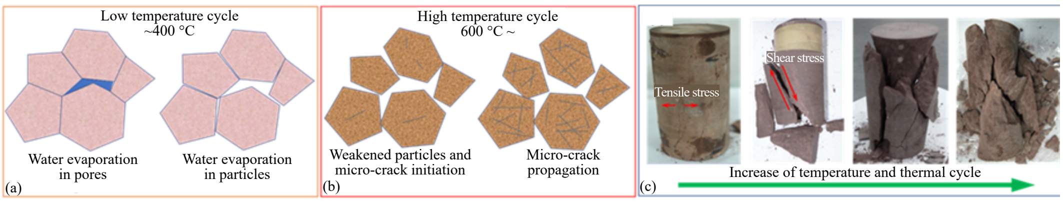

Figure 8. Diagrams of micro-structure development process under thermal cycle and failure pattern; (a) low temperature cycle, (b) high temperature cycle, and (c) failure pattern

The loss of free water occurs firstly and then the bound water is evaporated with the increasing of the thermal cycle. The mineral particle decomposition, quartz phase transition, and thermal expansion play a key role in the thermal cycle with a high temperature. As a result, the strength of mineral particles is weakened and the micro-cracks in mineral particles began to appear. With the increasing in the thermal cycle, a large number of cracks are initiated and propagated, and the crack network is formed inside the sandstone. The above changes are the main reason why the *P*-wave velocity decreases with the increase in the temperature and thermal cycle.

Figure 8(c) shows the failure patterns of the sandstone samples. The failure mode becomes more complex with the increase in the temperature and thermal cycle. The sandstone specimen at room temperature mainly presents the tensile failure. Then, the shear failure is induced after the low-temperature cycle. As temperature and number of cycles continue to increase, the mixed failure including the tensile failure and shear failure occurs. Obviously, the shear slip can reduce the ability to resist external loading and increase the dissipated energy. In addition, the larger the thermal cycle number is, the higher the crushing degree of the sandstone sample, which also greatly increases the dissipative energy and the proportion of dissipative energy.

Conclusion

The density, *P*-wave velocity and mechanical properties of the sandstone reduced with the increase in the thermal cycle, especially in the high temperature cycle. The increase of the temperature in the thermal cycle can increase the influence of the thermal cycle on the energy evolution law. The energy release was very rapid in the low temperature cycles, while it slowed down in the high temperature cycle. A threshold temperature in the thermal cycle was observed and its value is about 400 °C. Compared with the low temperature cycle, in the high temperature cycle the proportion of elastic energy significantly decreased and the proportion of dissipated energy always kept a relatively high level. The energy evolution law during the deformation and failure process was closely related to the failure modes of the sandstone.

Acknowledgment

This work had been financially supported by the Research Fund of the State Key Laboratory of Coal Resources and Safe Mining, CUMT (No. SKLCRSM19KF001), the State Key Laboratory for GeoMechanics and Deep Underground Engineering, China University of Mining & Technology (No. SKLGDUEK1905), the Key Laboratory of Deep Earth Science and Engineering (Sichuan University), Ministry of Education, (No. DESE201902), and the Jiangsu Province Science Foundation for Youths (No. BK20180653).

Nomenclature

E_u – elastical modulus, [GPa]
u^d – dissipation energy, [MJmm^{-3}]
u^e – elastic strain energy, [MJmm^{-3}]
u – total absorption energy, [MJmm^{-3}]

Greek symbols

ε^e – elasitc strain, [–]

ε – strain, [–]

σ – stress, [MPa]

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Paper submitted: May 3, 2020
Paper revised: July 17, 2020
Paper accepted: August 9, 2020