Experimental Research on Inhibition of temperature to inverse martensitic phase transformation of NiTi Shape Memory Alloy

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Abstract: The effects of temperature changes, load cycles, and amplitude changes on the mechanical properties of NiTi shape memory alloys such as the attenuation of energy dissipation capacity, equivalent damping ratio, and residual strain were studied experimentally. Experimental results show that: under different temperature and amplitude, the shape memory alloy achieves stable performance after 10 cycles, and the attenuation of energy dissipation capacity mainly occurs in the first 6 cycles; as the temperature decreases or the number of cycles increases, equivalent damping ratio tends to decrease; When the temperature decreases near the completion temperature of austenite transformation, the residual strain is significantly affected. Even if the strain amplitude is small, residual deformation accumulation will occur, inhibiting the occurrence of reverse martensite transformation, and it is not good for the super-elasticity of SMA.

1. Introduction
Shape memory alloy (SMA) is a functional material widely used in electronic equipment, automotive industry, medical equipment and other fields[1]. Normal temperature austenite phase shape memory alloy has super-elasticity at this temperature and is a good material for project of energy dissipation. Regarding the research on the properties of shape memory alloys, scholars at home and abroad have made a series of achievements in terms of temperature influence, cyclic loading, stress (strain) amplitude, and loading rate (frequency)[2-5]. Around shape memory alloy austenite transformation completion temperature \( A_f \), the increase in residual strain will inhibit the occurrence of inverse martensite transformation. The energy dissipation capacity of SMA decays rapidly in the first few cycles and becomes stable after several cycles[6].

The residual strain of SMA is closely related to temperature and loading amplitude[7]. The increase of strain amplitude will lead to the increase of residual strain. Increased residual strain will inhibit the occurrence of reverse martensitic phase transformation. The larger the residual strain of the shape memory alloy, the less its super-elasticity will be performed, and the less its energy dissipation performance will be exerted[8].

Regarding the study of the influence of temperature, most of the set temperature points exceed the austenite transformation temperature \( A_f \) by 15°C, and the research within 15°C is not thorough. Therefore, through experimental methods, three temperature points were set up to study the performance characteristics when the temperature was close to \( A_f \).
2. Experimental procedure

2.1 Experimental materials
The material used in the test is from Xi'an Siwei Metal Material Co., Ltd., which is a Ti-55.82at% Ni shape memory alloy with a diameter of 2mm. The austenite finish transition temperature \( T_f \) determined by DSC test is 10°C. The test set temperature points are 12°C, 18°C and 24°C.

The test is mainly to study the performance characteristics of shape memory alloys near the austenite transformation temperature \( T_f \). The main research contents are: the effect of temperature on the stress-strain relationship, the effect of temperature on residual strain, the effect of temperature on energy dissipation attenuation, and the effect of temperature on equivalent damping ratio.

| Numbering | Temperature (°C) | Strain amplitude | Loading speed  | Cycles |
|-----------|------------------|------------------|----------------|--------|
| ①         | 24               | 6.00%            | 50mm / min     | 15     |
| ②         | 18               | 6.00%            | 50mm / min     | 15     |
| ③         | 12               | 6.00%            | 50mm / min     | 15     |
| ④         | 12               | 4.12%            | 50mm / min     | 10     |

The test was completed in the Earthquake Engineering and Engineering Vibration Laboratory of the Institute of Engineering Mechanics, China Earthquake Administration. The experimental equipment used was SHT4206 microcomputer-controlled electro-hydraulic servo universal testing machine. The target of the loading section was displacement control, and the target of the unloading section was tension control.

![SMA and experimental loading](image)

3. Results and discussion

3.1 Constitutive model and typical parameters of hyperelastic SMA
Fig.2 shows the ideal constitutive model of the super-elasticity SMA, where \( \sigma_m, \sigma_M, \sigma_A \) and \( \sigma_A \) are the starting stress of martensite transformation, the ending stress of martensite transformation, the starting stress of austenite transformation, and the ending stress of austenite transformation; \( \varepsilon_{res} \)
is the residual strain; $\sigma_u$ and $\varepsilon_u$ are the maximum stress and maximum strain.; $\Delta W$ is the energy consumption of a single cycle of SMA, which is an important parameter for SMA to make engineering energy-consuming equipment.; and $W$ is the total strain energy in a single cycle of SMA. The calculation method of the equivalent damping ratio is:

$$\xi_{eq} = \frac{1}{4\pi} \frac{\Delta W}{W}$$  \hspace{1cm} (1)

In this paper, the effects of temperature change and load cycle on the energy dissipation capacity attenuation range, equivalent damping ratio, and inverse phase transformation of SMA martensite are studied.

Fig.2. Constitutive model of super-elasticity SMA

3.2 Attenuation of energy dissipation capacity

Fig.3. Stress-strain curve at 24℃
Fig. 3, Fig. 4 and Fig. 5 are the stress-strain curves of SMA at 24°C, 18°C and 12°C. After 10 cycles, the SMA’s performance has stabilized, defining the attenuation of the energy dissipation capacity of the nth cycle as:

\[ \delta_n = \frac{\Delta W_n - \Delta W_{n-1}}{\Delta W_1 - \Delta W_{15}}, \quad (2 \leq n \leq 15) \]  

(2)

\( \Delta W_1 \), \( \Delta W_{15} \) is the energy dissipation capacity of the first cycle and the 15th cycle, and \( \delta_n \) can reflect the nonlinear relationship between the attenuation of energy dissipation capacity and the number of cycles.
Fig. 6. Attenuation of energy dissipation capacity with the cycle

Fig. 6 is the attenuation of energy dissipation capacity with the cycle, the attenuation of the energy dissipation capacity of the SMA is large in the first few cycles. At 24℃, 18℃, and 12℃, the energy attenuation of the second cycle is 44.74%, 28.24% and 22.15%, the energy attenuation of the first six cycles is 71.70%, 61.31%, and 74.12%, so the energy attenuation mainly occurs in the first six cycles; the energy change of the two adjacent cycles is within 5% when it is stable. Therefore, in order to obtain a stable energy-dissipating SMA, a certain number of training is necessary.

3.3 Equivalent damping ratio

As shown in Fig. 7, the equivalent damping ratios of 24℃ and 18℃ differ by about 0.05 under the same strain amplitude, and the energy dissipation capacity of SMA is better at 24℃, as the number of cycles increases, both it gradually decreases, but the reduction is not obvious. At 12 ℃, the residual strain accumulation speeds up and the equivalent damping ratio rapidly decays. After 15 cycles, the equivalent damping ratio $\xi_{eq}$ is only 0.021, this is because of the accumulation of residual strain inhibits the inverse phase transformation of SMA martensite. As a result, the yield platform disappears.
and the material undergoes elastic unloading of martensite.

4. Inhibition of low temperature cycling on reverse phase transformation of SMA

According to the tensile-unloading cycle test with an amplitude of 6%, the strain corresponding to the normal martensitic transformation at 12°C is about 4.5%. Therefore, the tensile-unloading test with an amplitude of 4.12% is performed. After 10 cycles, the result is shown in the Fig.

As shown in Fig. 8, the shape memory alloy still shows a large residual strain under a load cycle of 4.12% amplitude, and the relationship between the residual strain and the cycle is shown in Fig.9.

![Fig.8. 4.12% amplitude stress-strain curve at 12°C](image)

As shown in Fig. 8, the shape memory alloy still shows a large residual strain under a load cycle of 4.12% amplitude, and the relationship between the residual strain and the cycle is as shown Fig. 9. In the first three cycles, there is little difference in the residual strain under the two amplitude cycles. In the fourth cycle, the residual strain with a magnitude of 4.12% strain is stabilized in advance, and the stable residual strain value is 2.46%. It can be seen that when the temperature is close enough to the completion temperature of martensite phase transformation, even if the strain amplitude is small, SMA will also show large residual deformation, and the accumulation of residual deformation will make the stress-strain curve long and narrow.

![Fig.9. Relationship between cyclic amplitude and residual strain](image)
5. Conclusion
At different temperatures, the attenuation of SMA's energy dissipation capacity is mainly concentrated in the first 6 cycles. After the performance is stable, the energy dissipation capacity of the adjacent two cycles changes within 5%, which can provide stable energy-dissipating for the project; under low temperature conditions, the material is more prone to the accumulation of residual strain, inhibits the occurrence of reverse martensite transformation, and the equivalent damping ratio rapidly decays; under low temperature conditions, large residual deformation will occur even if the strain amplitude is small, and residual strain is closely related to strain amplitude.

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