ISSN 2616-5767 Vol.8, Issue 2: 76-83, DOI: 10.25236/AJETS.2025.080210

Experimental Study on Mechanical Properties and Recovery Properties of NiTi SMA

Yutong Zha[1,a,*], Qiwen Xue[1,b], Gang Wang[1,c]

[1]School of Traffic Engineering, Dalian Jiaotong University, Dalian, Liaoning, 116028, China
[a]15833563730@163.com, [b]xueqiwen@djtu.edu.cn, [c]wanggang_1977@163.com
**Corresponding author*

Abstract: *This paper addresses the issue of the mechanical properties of NiTi shape memory alloy (NiTi SMA) as a driving material being unclear. It begins from the standpoint of active temperature control and uses differential scanning calorimetry (DSC) and uniaxial tensile testing to evaluate the performance of NiTi SMA under various working conditions. The stress-strain characteristics and thermal reversible properties of NiTi shape memory alloys (SMA) at various loading rates, distinct SMA configurations, and varying strain amplitudes were examined through experimental methods.From the analysis of the test results, it can be seen that NiTi SMA exhibits similar mechanical properties under different working conditions, while NiTi SMA will produce recovery stress when it is heated, and it is positively correlated with temperature.*

Keywords: *Shape Memory Alloy, Recoverability, Mechanical Property, Uniaxial Tension*

1. Introduction

Shape memory alloys typically consist of two or more metallic components, possessing remarkable mechanical characteristics, resistance to corrosion, and distinct recovery behaviors, making them recognized as some of the most outstanding functional materials[1].As a result, shape memory alloys find extensive applications in various domains, including aerospace, electronic devices, construction engineering, and other sectors.Investigating the mechanical characteristics and recoverable behaviors of shape memory alloys holds substantial theoretical and applied importance[2-4].

NiTi SMA is a typical driving material, and its mechanical properties are complex, which attracts many scholars to study.Wang et al.[5]conducted a temperature-rising tensile test on NiTi SMA. When the temperature increased from 25°C to 100°C, the performance of SMA was significantly enhanced, and the recovery ability reached more than 98 % of the original shape. However, there is no specific study on the recoverable performance of NiTi SMA during heating.Zhang et al.[6]investigated the influence of varying activation temperatures, extra loads, and environmental temperatures on the recovery stress of shape memory alloys, as well as examined the uniaxial tensile mechanical behaviors of SMA rods following exposure to elevated temperatures. The findings indicate that following exposure to elevated temperatures, the stress of the SMA rod exceeds its initial stress owing to the shape memory effect, while its elastic modulus and maximum strength stay relatively constant. However, there is no comprehensive study of various possible factors affecting the mechanical properties of SMA. Owing to the temperature-dependent properties of shape memory alloys (SMA), variations in strain amplitudes and heating temperatures can result in disparities in both the magnitude and the trend of prestress changes. Hence, numerous issues remain to be thoroughly investigated regarding the temperature-dependent mechanical characteristics of NiTi shape memory alloys.

Building on the aforementioned factors, to further explore the temperature-dependent mechanical behavior of NiTi shape memory alloys, this study primarily focuses on the shape memory effect induced by temperature-driven martensitic transformation and its reverse process in the material, and the principle that NiTi SMA wire will generate recovery force under the constraint condition when heating up. The mechanical behaviors of shape memory alloys under varying strain amplitudes, loading velocities, and wire dimensions are examined, alongside a discussion on the impact of temperature on the recovery characteristics of SMA. The pertinent theoretical information may offer guidance for the practical utilization of shape memory alloy materials.

ISSN 2616-5767 Vol.8, Issue 2: 76-83, DOI: 10.25236/AJETS.2025.080210

2. Uniaxial Tensile Mechanical Properties of SMA

2.1. Material Selection and Experimental Design

Nickel-titanium shape memory alloy wires with diameters of 0.6 mm and 1.0 mm, manufactured by Gaoan Memory Alloy Materials Co., Ltd., were chosen for the experiment.The proportions of Ni and Ti in the two varieties of NiTi SMA wires are 51% and 49%, correspondingly.Based on the data supplied by the producer, the phase transition temperature and chemical properties of the wire meet the requirements of the specification GB / T39989-2021. The specific parameters are shown in Table 1.

Table 1: Typical material performance parameters of NiTi SMA.

Material parameter	Performance index
Density(g/cm^3)	6.4-6.5
Melting point(℃)	1310
Elastic modulus(GPa)	83
Tensile strength(MPa)	850
Yield strength(MPa)	690
Elongation(%)	10
Maximum recovery strain(%)	8
Maximum recovery stress(MPa)	600
Poisson ratio	0.33
Restoring force(MPa)	436.5

The test used an electronic universal testing machine produced by Jinan Wenteng Test Instrument Co., Ltd., and used conventional strain gauges and Donghua data acquisition instrument to collect information. The initial measuring length of the sample is 200 mm, and the rate of displacement remains unchanged throughout the loading procedure, with the sample being extended until rupture occurs. In the process of testing, it is necessary to control the SMA wire to be quasi-static, and pay attention to grinding the two clamping ends of the wire with sandpaper and wrapping it with insulating tape to prevent the wire from slipping. The objective of this study is to evaluate the tensile strength of SMA wire, as well as to examine the impact of strain amplitude, loading speed, and SMA wire parameters on its tensile mechanical characteristics. The specific test scheme is designed as Table 2.

Table 2: Tensile test design scheme of SMA.

Working condition	Specimen	Original gauge length(mm)	Loading rate(mm/min)	Strain amplitude	Diameter of SMA(mm)
1	SMA-1-1-F	200	1	-	1
	SMA-0.6-1-F	200	1	-	0.6
2	SMA-1-1-F	200	1	7%	1
	SMA-1-2-F	200	2	7%	1
	SMA-1-5-F	200	5	7%	1
	SMA-1-10-F	200	10	7%	1
	SMA-1-20-F	200	20	7%	1
	SMA-1-30-F	200	30	7%	1
3	SMA-0.6-1-2%	200	1	2%	0.6
	SMA-0.6-1-3%	200	1	3%	0.6
	SMA-0.6-1-4%	200	1	4%	0.6
	SMA-0.6-1-5%	200	1	5%	0.6
	SMA-0.6-1-6%	200	1	6%	0.6
	SMA-0.6-1-7%	200	1	7%	0.6
	SMA-0.6-1-4%	200	1	4%	1
	SMA-1-1-5%	200	1	5%	1
	SMA-1-1-6%	200	1	6%	1
	SMA-1-1-7%	200	1	7%	1
	SMA-1-1-8%	200	1	8%	1
	SMA-1-1-9%	200	1	9%	1
4	SMA-0.6-1-4%	200	1	4%	0.6
	SMA-0.6-1-6%	200	1	6%	0.6
	SMA-1-1-4%	200	1	4%	1
	SMA-1-1-6%	200	1	6%	1

ISSN 2616-5767 Vol.8, Issue 2: 76-83, DOI: 10.25236/AJETS.2025.080210

2.2. Experiment Results and Analysis

2.2.1. Uniaxial Tensile

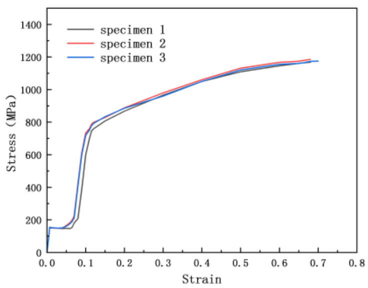
Based on the layout presented in Table 2 of the preceding section, the outcomes of steady tension tests on NiTi SMA wires with two different diameters can be acquired. In Figure 1 (a) and (b), the NiTi SMA wires with diameters of 0.6 mm and 1.0 mm are steadily elongated at a loading speed of 2 mm/min under ambient temperature conditions until the test specimens fail. Comparing the two figures in figure 1, it can be seen that the two wires with different diameters have the same mechanical properties.

The initial phase is the elastic region. From the start of the experiment until the stress in the SMA wire reaches the threshold stress for the phase change, the stress value lies between 0 and 140 MPa, with the strain approximately at 1%. In this stage, if the tension is removed, the deformation will be completely restored in theory.

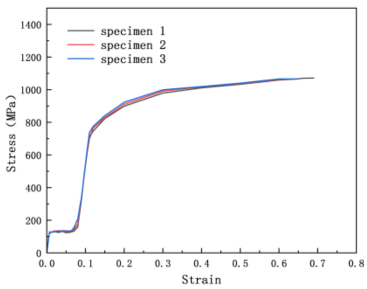
The subsequent phase represents the stage of phase transformation.The applied tensile force on the SMA wire surpasses the threshold stress for phase transition, resulting in the martensitic transformation. During this period, the stress growth stagnates and the strain continues to increase.The stress stable section of the 0.6mm wire is slightly higher than that of the 1.0mm SMA wire. The stress stable section of the former phase transition stage is about 140MPa, while the latter is stable at 120 ~ 130MPa, and the corresponding strain is usually increased from 1 % to about 5 %.

The third stage is the strengthening stage. During this phase, the NiTi SMA wire has undergone the complete phase change, and its resistance to deformation is reinstated, leading to an increase in stress as strain rises.This phase can be separated into two segments: the strengthening portion I, where the strain spans from 5% to 11%, the stress ranges from approximately 120 to 700 MPa, and the curve's gradient closely resembles that of the elastic phase. In the reinforcement phase II, the strain interval lies between 11% and 60%, with the stress varying from approximately 700 to 1100 MPa.The slope of the curve is significantly smaller than that of the strengthening section I, and there is an obvious inflection point between the two sections.

The concluding phase is the rupture stage, where the NiTi shape memory alloy wire experiences an overall strain exceeding 0.6.Due to the high ductility of SMA, after the stress level reaches the peak, local necking occurs in the weak parts of SMA wire, and the deformation continues to increase, but the stress decreases steadily until it is destroyed.



(a)0.6mm SMA tensile fracture



(b)1mm SMA tensile fracture

Figure 1:Monotonic tensile stress-strain curves of SMA wire.

2.2.2. Loading Rate

Figure 2 illustrates the stress-deformation curve of a 1mm SMA wire subjected to varying loading speeds. Under the scenario of a 7% strain amplitude, when the loading speed ranges from 1mm/min to 10mm/min, the stress-deformation curve of the SMA wire exhibits a distinct stress equilibrium region, and when the loading rate increases to more than 10mm / min, the stress stability section of the stress-strain curve gradually shows a trend of oblique upward development. Furthermore, the stress of the SMA wire entering the reinforcement phase, which refers to the stress value at the conclusion of the wire's phase transformation, will progressively rise as the loading speed increases.

ISSN 2616-5767 Vol.8, Issue 2: 76-83, DOI: 10.25236/AJETS.2025.080210

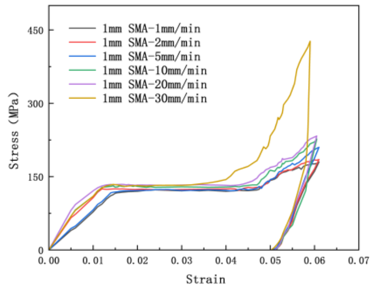
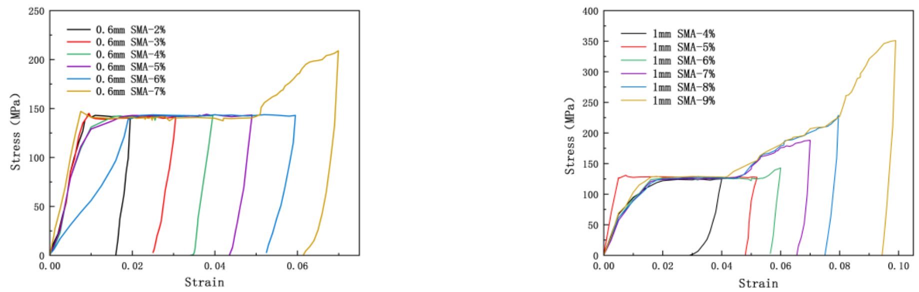


Figure 2:Monotonic tensile stress-strain curves of SMA wire with different loading rates.

2.2.3. Strain Amplitude

Figure 3 presents the stress-deformation plots of NiTi SMA wires with two distinct diameters throughout the entire monotonic tension process under various strain amplitudes.Generally, the stress of NiTi SMA exhibits a three-phase growth pattern as the strain amplitude rises: when the strain lies between 0 and 1.5%, the stress escalates rapidly with the augmentation of strain; when the strain ranges from 1.5% to 7%, the stress does not exhibit a notable increase and nearly remains unchanged; when the strain exceeds 7%, the stress displays a swift rise, and the growth rate increasingly resembles that of the initial stage of growth as the strain amplitude increases.Within the domain of moderate and low strain amplitudes (＜7%), the stress-strain development characteristics of the SMA wire remain comparatively constant. The stress stability at this phase does not show a considerable rise as the strain amplitude increases, maintaining a relatively steady state.This finding indicates that within this interval, the strain amplitude exerts minimal influence on the martensitic transformation stress of SMA.Nevertheless, once the strain amplitude rises to a greater range (7% ~ 9%), the stress shows a significant upward trend because the NiTi SMA wire enters the strengthening stage and is accompanied by the process of martensite hardening.



(a) 0.6mm SMA-1mm/min *(b) 1mm SMA-1mm/min*

Figure 3:Monotonic tensile stress-strain curves of SMA wires with different strain amplitudes.

Specifically, the stress stability section of 0.6mm wire in the range of 2 % ~ 6 % strain amplitude is maintained at about 140 MPa.When the strain amplitude reaches 7 %, the stress stability section of the stress-strain curve is shortened, and the back section shows a trend of oblique upward development, and the stress reaches 200 MPa. No significant alteration is observed in the stress stability region of the 1mm wire within the 4% ~ 6% strain amplitude range, remaining consistent between 120 and 130 MPa.When the strain amplitude is increased to 7 % ~ 9 %, the SMA wire slowly enters the strengthening stage, and the stress stable section in this process is reduced. As the stress amplitude continues to increase, the stress level progressively increases, with its rate of growth steadily accelerating. When the strain amplitude is 9 %, the stress is as high as 350 MPa.

Moreover, the residual strain of the SMA wire also grows as the strain amplitude is enhanced, however, all residual strain values stay beneath 1% of the respective strain amplitude, primarily distributed within the 0.5% ~ 1% range.This is primarily attributed to the martensitic phase change in the NiTi SMA wire once it enters the inelastic phase, leading to the residual strain in the NiTi SMA wire, where the deformation cannot be fully reversed. Only by heating the NiTi SMA wire from austenite to martensite can the deformation be recovered.

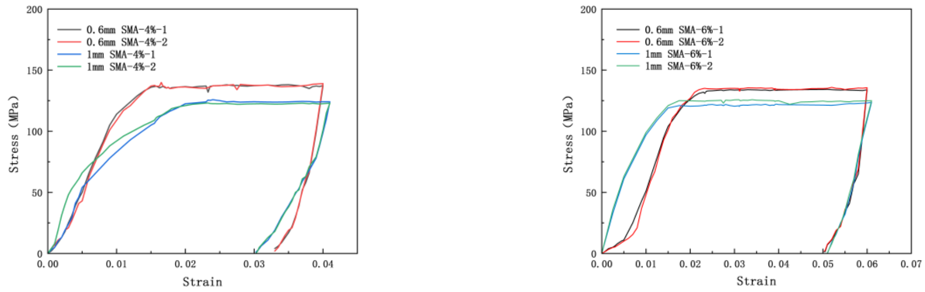
Furthermore, the strain amplitude exerts a significant effect on the energy dissipation capability of

ISSN 2616-5767 Vol.8, Issue 2: 76-83, DOI: 10.25236/AJETS.2025.080210

SMA wires.It can be seen from the figure that the hysteresis loop area formed by the SMA wire continues to expand with the increase of the strain amplitude. When the strain amplitude ranges from 2% to 6%, the region enclosed by the hysteresis curve is almost linearly expanded, resulting in a nearly fourfold increase in the energy dissipation capacity of the NiTi SMA wire, this underscores the profound impact of the strain amplitude on the energy dissipation ability of the SMA wire.

2.2.4. Diameter of SMA

Based on the various wire diameter design plans outlined in Table 2, the outcomes presented in Figure 4 (a) and (b) can be derived. At a loading rate of 1mm/min, both 0.6mm and 1mm NiTi SMA wires exhibit identical mechanical characteristics. Through a comparison of the stress-strain diagrams for NiTi SMA wires with varying diameters at strain amplitudes of 4% and 6%, It is evident that the stress stability of the 0.6mm SMA wire during the phase transition stage exceeds that of the 1mm SMA wire.In detail, the stress stability level of the phase transition section of 0.6mm SMA wire is about 140MPa, while the stress stability level of 1mm SMA wire is about 120 ~ 130MPa.



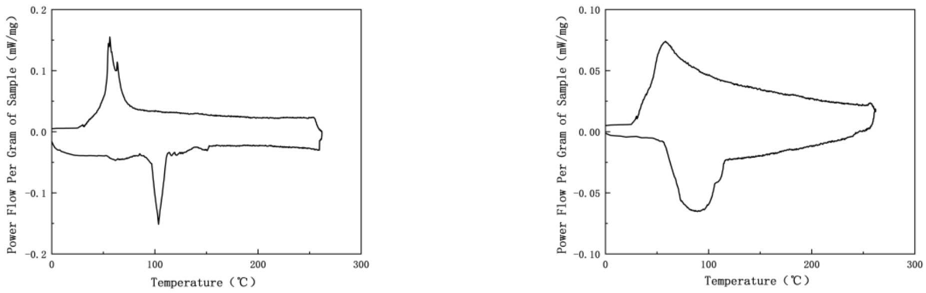
(a) SMA-4%-1mm/min *(b) SMA-6%-1mm/min*

Figure 4:Monotonic tensile stress-strain curves of SMA wires with different diameters.

3. Heat Recovery Performance of SMA

3.1. DSC Test

Before the SMA heating tensile test,It is essential to identify the four key phase transition temperature points of the NiTi SMA wire employed in this study: the start temperature of martensitic transformation (Ms) and its finish temperature (Mf), additionally, the start temperature of the austenite phase transition (As) and its finish temperature (Af) must be determined to confirm if the wire qualifies as an SME-type NiTi shape memory alloy wire, so that its good shape memory effect can be effectively utilized to study its recovery performance after heating. Therefore, DSC tests were performed on the 0.6mm and 1mm NiTi SMA wires used in the experiment, and the results were shown in Figure 5. The specimen was warmed from ambient temperature to 250°C at a pace of 5°C per minute and held at a steady temperature for 5 minutes. Subsequently, the specimen was gradually cooled to ambient temperature at a rate of 5°C per minute and kept at a stable temperature for 5 minutes.



(a)0.6mm NiTi SMA DSC test *(b)0.6mm NiTi SMA DSC test*

Figure 5:NiTi SMA DSC test.

In order to determine the specific value of the transition temperature, two tangents of the curve are drawn in the diagram, and the intersection of the two tangents is made as a vertical line falling on the x-

ISSN 2616-5767 Vol.8, Issue 2: 76-83, DOI: 10.25236/AJETS.2025.080210

axis. The point where the curve intersects is identified as the transition temperature of the phase change[7].It can be determined that the initiation temperature of the martensitic transformation for the 0.6mm NiTi SMA wire is 70.91°C, while its conclusion temperature is 41.43°C, The initiation temperature of the austenite transformation is 95.37°C, whereas its conclusion temperature reaches 119.77°C.The initiation temperature of the martensitic transformation for the 1mm NiTi SMA wire is 93.69°C, while its final temperature is 45.16°C.The onset temperature of the austenite transformation is 60.01°C, and the completion temperature is 116.49°C, which satisfies the criteria for the following experiments.

3.2. Test Design and Preparation

During the assessment of the recovery characteristics of NiTi SMA wire, the wires with diameters of 0.6mm and 1mm were again chosen for evaluation.After pre-stretching the NiTi SMA wire, the two ends of the wire are fixed and heated. At this time, the recovery stress will be generated due to the constraint.In light of this concept, the correlation between the wire's temperature and its stress-strain behavior is analyzed.For NiTi SMA wire with a 0.6mm diameter, three distinct pre-strain levels were established, specifically 2%, 4%, and 6%, correspondingly. For NiTi SMA wire with a 1mm diameter, three different sets of pre-strain values were defined, namely 4%, 6%, and 8%[8], and the specific test scheme is shown in Table 3. The entire procedure of NiTi SMA wire's stress variation with temperature is documented. Additionally, the peak stress value that NiTi SMA wire can attain at the associated steady temperature is identified.

In this experiment, the heating technique via spray gun was employed to acquire the recovery stress, while a thermometer was utilized to continuously monitor the wire's temperature. During the test, special insulation cotton was used to keep the wire warm to prevent heat diffusion and increase the test error.Furthermore, it is important to ensure that the spray gun is activated first to heat the specimen, and the thermometer is employed to gauge the specimen's temperature, continuing until the wire attains the desired temperature before initiating the experiment, and the test process must maintain a relatively stable temperature environment.

Table 3: Heating recovery test design scheme of SMA.

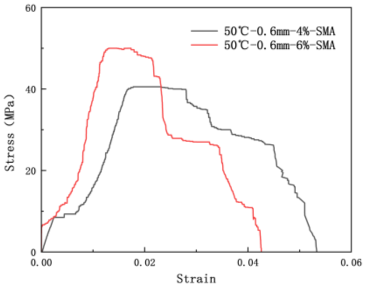
Working condition	Specimen	Diameter of SMA(mm)	Strain amplitude	Heating steady temperature(°C)
1	SMA-0.6-4-50	0.6	4%	50
	SMA-0.6-6-50	0.6	6%	50
	SMA-1.0-4-50	1.0	4%	50
	SMA-1.0-6-50	1.0	6%	50
2	SMA-1.0-4-100	1.0	4%	100
	SMA-1.0-6-100	1.0	6%	100
	SMA-1.0-4-200	1.0	4%	200
	SMA-1.0-6-200	1.0	6%	200
	SMA-0.6-4-100	0.6	4%	100
	SMA-0.6-6-100	0.6	6%	100

3.3. Experiment Results and Analysis

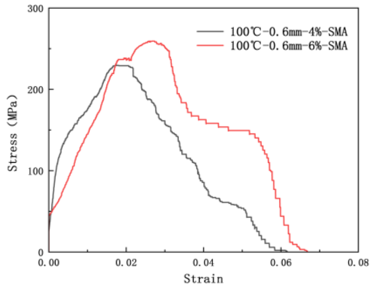
The stress-strain curves of 0.6mm and 1mm NiTi SMA wires at different temperatures and different pre-strain levels are shown in Figure 6.It can be seen from the figure that when the heating temperature is 50 °C, the maximum stress of NiTi SMA wires with diameters of 0.6 mm and 1.0 mm does not exceed 50 MPa, and when the heating temperature is 100 °C and 200 °C, the maximum stress of the two NiTi SMA wires is very close.

In particular, when the heating temperature reaches 100 °C, with strain amplitudes of 4 % and 6 %, the peak stress of 0.6mm NiTi SMA wire is 229MPa and 259MPa, while the maximum stress of 1mm NiTi SMA wire is 287MPa and 300MPa, respectively.When the heating temperature reaches 200 °C, the maximum stress of 0.6mm NiTi SMA wire is 233MPa, 260MPa, and the maximum stress of 1mm NiTi SMA wire is 292MPa and 300MPa at 4 % and 6 % strain amplitudes, respectively.This suggests that once the temperature surpasses the final temperature of austenite phase transformation, the increase in recovery stress of NiTi SMA wire becomes minimal.Moreover, as the pre-stretching strain level rises, the peak recovery stress of the NiTi SMA wire similarly escalates.

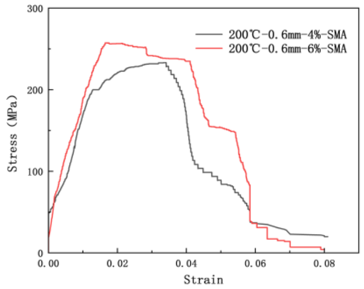
ISSN 2616-5767 Vol.8, Issue 2: 76-83, DOI: 10.25236/AJETS.2025.080210



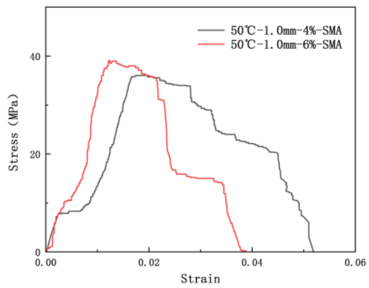
(a) 0.6mm NiTi SMA-50℃



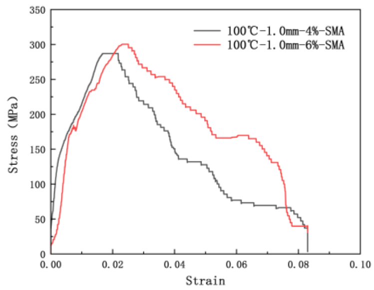
(b) 0.6mm NiTi SMA-100℃



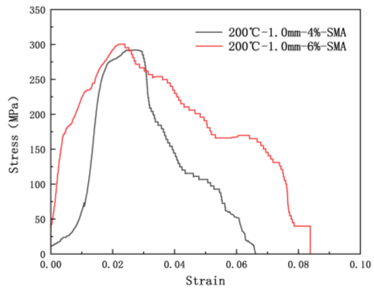
(c) 0.6mm NiTi SMA-200℃



(d) 1mm NiTi SMA-50℃



(e) 1mm NiTi SMA-100℃



(f) 1mm NiTi SMA-200℃

Figure 6:Thermal tensile tests stress-strain curves of 0.6mm and 1mm NiTi SMA wires.

4. Conclusion

This study explores the tensile characteristics of NiTi SMA wires under various conditions, as well as the correlation between temperature and stress-strain behavior during the heating process. The mechanical properties and temperature recovery properties of NiTi SMA wires are analyzed.

1) At room temperature, SME-type nickel-titanium shape memory alloy wires show similar mechanical properties under different influencing factors.By analyzing the correlation between stress and strain of NiTi SMA wire under three distinct influencing factors, it is found that the strain amplitude has the most pronounced effect.An increased strain amplitude will notably raise the stress in NiTi SMA wire, while the residual strain will also experience an increase.

2) In the heating state, NiTi SMA wire will produce recovery stress.The recovery stress of NiTi SMA wire tends to rise as the temperature increases.However, once the temperature surpasses the final transformation temperature of the austenite phase, the increase in recovery stress becomes quite minimal.

References

[1] Wang Benli. Research and application progress of NiTi shape memory alloy [J].New material industry, 2021, (04) : 28-31.
[2] Wu Z S, Wang X, Wu G, et al. FRP reinf-orced engineering structural systems [M]. Science

ISSN 2616-5767 Vol.8, Issue 2: 76-83, DOI: 10.25236/AJETS.2025.080210

press,2017: 10-18. (in Chinese)

[3] Zheng Yuzhou, Wang Wenwei, Mosalam Khalid M., et al. Experimental investigation and numerical analysis of RC beams shear strengthened with FRP/ECC composite layer[J]. Composite structures,2020,246(Aug.):112436.1-112436.14.

[4] Zhou, Yingwu, Gao, Heng, Hu, Zhiheng, et al. Ductile, durable, and reliable alternative to FRP bars for reinforcing seawater seasand recycled concrete beams: steel/FRP composite bars[J]. Construction and Building Materials,2021,269(Feb.1):121264.1-121264.13.

[5] Wang, X., Zhang,X., & Li,J.(2020). Experimental and numerical analysis of the mechanical properties of NiTi alloy at different temperatures[J]. Materials Science and Engineering: A, 771, 138538.

[6] Zhang Yaowen. Effect of temperature on recovery stress and mechanical properties of iron-based shape memory alloys [J].Functional materials, 2024,55 (09) : 9022-9030.

[7] Tan Xiao.Study on the basic mechanics and recoverable properties of FRP / SMA composites [D]. Southeast University, 2019.

[8] HUO Hui-Yingxin, XUE Yan-jie, WANG Wen-wei, DAN Xiao. Experimental study on mechanical properties and recoverable properties of FRP / shape memory alloy composites [J].Composite Materials, 2023,246 (9) : 5302-5314.