Submitted: March 4, 2024 Revised: March 19, 2024 Accepted: April 8, 2024

Martensite stabilization effect after high strain rate loading

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ABSTRACT

The behavior of shape memory alloys depends on the deformation technique and strain rate. This paper aims to demonstrate the martensite stabilization effect in equiatomic NiTi shape memory alloy after high strain rate loading. The high strain rate deformation at different rates and temperatures was performed using the Kolsky method modified for tension. Quasistatic deformation tests were conducted on a universal testing machine at identical temperatures up to the same residual strains. After tests, the samples were heated through reverse martensitic transformation temperature range in a thermomechanical analyzer with a temperature measurement accuracy of 0.3 °C. It is shown that the martensite stabilization effect depends on the loading rate in martensitic, premartensitic, and mixed phase states. An increase in the loading rate in the martensitic state results in a greater stabilization effect. High strain rate loading in the premartensitic and mixed-phase states does not lead to martensite stabilization, unlike in the quasi-static case. The results are consistent with the those of other authors and can be explained by hypotheses referenced in the paper.

KEYWORDS

shape memory alloys • nickel titanium • martensite stabilization effect • high-strain rate loading

Acknowledgements. *Research was performed using the Centre for Thermogravimetric and Calorimetric Research of the Research Park of St Petersburg State University. The work was supported by Russian Science Foundation (project no. 22-79-00068).*

Citation: Ostropiko ES, Konstantinov AYu. Martensite stabilization effect after high strain rate loading. *Materials Physics and Mechanics*. 2024;52(2): 49–55.
http://dx.doi.org/10.18149/MPM.5222024_5

Introduction

Shape memory alloys (SMAs) are the special type of smart materials [1]. They have been used in various fields, including engineering [2–5], medicine [6–8], and aerospace technology [9–12]. The NiTi (Nickel Titanium) alloy is the most well-known and studied SMA due to its superior properties, including high strength, biocompatibility, corrosion resistance, and most importantly, the superior shape memory effect (SME). SME is the ability of a deformed alloy to return to its "remembered" pre-deformed shape when heated. The mechanism of the SME is due to the thermoelastic reversible martensitic phase transformation that can be activated by temperature change and loading/unloading [13].

The mechanical and functional behavior of the material depends on the deformation technique and on the strain rate. Researchers have long been interested in the influence of strain rate on the SMAs, and research has focused on their mechanical properties, structures and functional behavior [14–21]. The reason for the high interest in the behavior under the high strain rate loading is clear. For example, SMAs have a high damping capacity due to stress-induced martensite phase transformation or martensite

Publisher: Peter the Great St. Petersburg Polytechnic University

reorientation, which makes them ideal for use in damping devices [22]. However, the phase transformation is not perfectly thermoelastic and is sensitive to the strain rate. Moreover, the thermoelastic martensitic transformation itself has a unique property known as the martensite stabilization effect (MSE). After deformation, the reverse martensitic transformation start temperature (A_s) increases, according to the Clausius-Claiperon equation. This effect has been widely studied for various compositions [23], and prestrain methods [24]. The microstructural approach was used to model the martensite stabilization effect [25]. However, no clear explanation for this phenomenon has appeared, although there are several hypotheses. For instance, in [26], the authors proposed the following hypothesis to explain the effect. They proposed a new mechanism for the MSE, suggesting that damage to the martensite boundaries during pre-strain decreases their mobility. As a result, a greater thermodynamic force (overheating) is required to move the interfaces during the reverse martensitic transformation.

Although the stabilization effect has been extensively studied, there are no works demonstrating this phenomenon after high strain rate loading. This work shows the peculiarities of the martensite stabilization effect after deformation at various rates and temperatures. It was discovered that the realization of this effect, as well as functional and mechanical behavior, is also dependent on the loading rate. The presented results are consistent with the hypothesis mentioned above.

Methods

Equiatomic NiTi, the most popular shape memory alloy, was selected for the investigation. Samples with a working part's height and diameter of 8 mm were manufactured using a CNC machine. Residual stresses were removed by subsequent aging at 500 °C for 1 hour, followed by cooling in a furnace. After heat treatment, the material demonstrated a single-step B2-B19' transformation with characteristic temperatures of M_s = 78 °C, M_f = 55 °C, A_s = 89 °C and A_f°= 110 °C. The results of different scanning calorimetry are shown in Fig. 1.

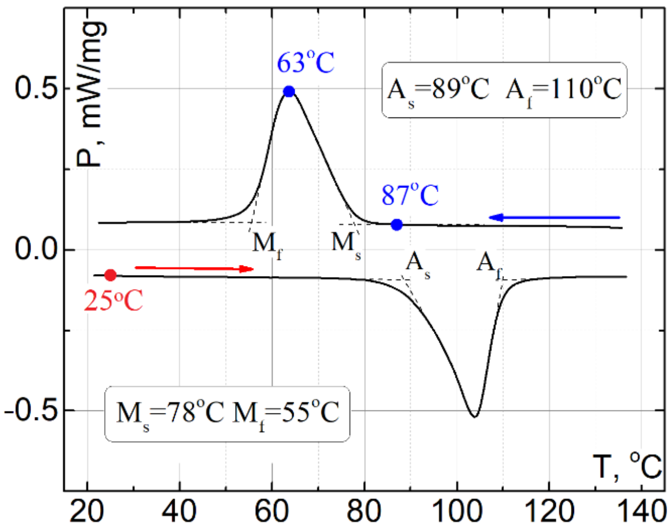

Fig. 1. Calorimetric curve of the material (●, ● - test temperatures)

The following test temperatures were chosen: 25, 87, 63 °C (marked with dots in Fig. 1). The temperatures of 87 and 63 °C were achieved by cooling from the high-temperature austenitic state, from 140 °C. At 87 °C the material was in the "pre-martensitic" state, close to the martensite start temperature M_s. At 63 °C, which corresponds to the peak in the calorimetric curve, the material was in the mixed-phase state. At room temperature (25 °C) the material was in a pure martensitic state.

High strain rate loading was performed using a Kolsky method for a split Hopkinson pressure bar [27] modified for tension mode [28,29]. Figure 2 illustrates the experimental setup. To conduct tests at elevated temperatures, a small tubular oven was placed at the edges of the bars with the specimen in between, and temperature control was provided by a thermocouple. Test parameters (stress, strain in the specimen, load, strain rate, loading time) were automatically calculated using the Kolsky formulae based on data obtained from low-base foil strain gauges placed on the surfaces of the bars. Further details can be found in [29].

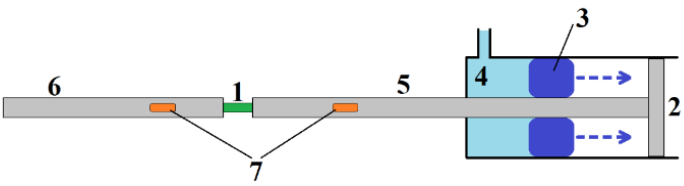

Fig. 2. Scheme of Kolsky method modified for tension: 1 – specimen; 2 – anvil; 3 – striker; 4 – compressed air; 5,6 – measuring bars; 7 – strain gauge

Residual strains were measured after the deformation and cooling to room temperature. Due to the peculiarities and limitations of the loading method, achieving higher strain rates resulted in higher residual strains in the specimens. Residual strains were approximately 5, 10 and 15 % after deformation at strain rates of ≈ 500, 1000, and 1500 sec^{-1}, respectively.

The universal testing machine equipped with a thermal chamber was used to perform quasistatic deformation up to the residual strains at the test temperatures.

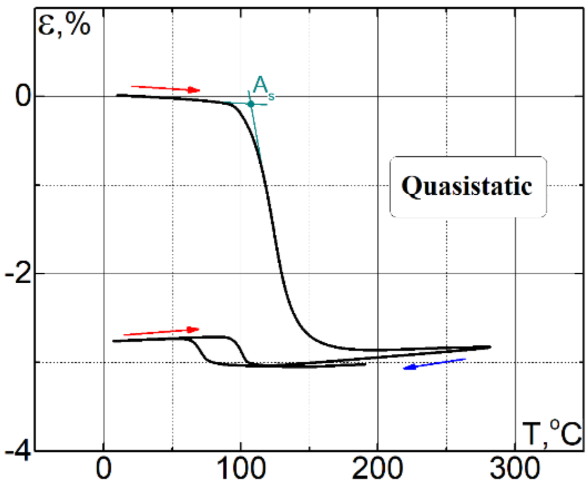

Fig. 3. Determination of reverse martensitic transformation start temperature A_s. As an example, a specimen deformed quasistatically to 5 % residual strain at a strain rate of 500 s^{-1} is shown

After tests, the specimens were thermocycled through the temperature range of the direct and reverse martensitic transformation in a thermomechanical analyzer with a temperature measurement accuracy of 0.3 °C. The rate of temperature change was about 1.5 °C per minute. The reverse martensitic transformation start temperatures A_s were measured by the tangent method, at the moment when the strain recovery curves on heating deviated from a straight trajectory, as shown in the example in Fig. 3. The paper focuses on the A_s, without considering the mechanical and functional features that appear with high-strain rate loading.

Results and Discussion

At room temperature, the material is in the martensitic state. When subjected to external load, the material accumulates reversible strain due to martensite reorientation and irreversible plastic strain. However, the increase of loading rate in the martensitic state leads to the increase of irreversible strain and decrease of reversible strain [30]. From the experimental data presented in Fig. 4, it can be seen that in both cases, the martensite stabilization effect increases as the total residual strain $\boldsymbol{\varepsilon}_{res}$ increases, but the difference in the proportions of reversible and irreversible strains in the quasi-static and dynamic cases leads to a difference in the stabilization effect. The higher loading rate results in a higher proportion of irreversible strain compared to the quasistatic case, which leads to a greater difference in the stabilization effect. According to results a stronger MSE is correlated with an increase in irreversible plastic deformation. Higher plastic strain leads to an increase in strain inconsistency, which reduces the mobility of martensitic boundaries. As a result, a greater thermodynamic force is required for the reverse martensitic transformation to occur.

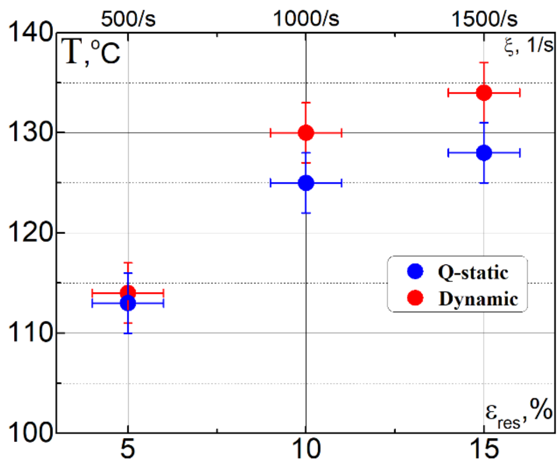

Fig. 4. The values of As in the first heating after tests at room temperature in the martensitic state depend on the strain rate ξ and the residual strain ε_{res} (● – after quasistatic deformation; ● – after high strain rate loading)

As mentioned above, martensitic transformation in shape memory alloys can be activated not only by temperature change but also by loading/unloading. The transition from one phase to another is accompanied by the absorption or release of heat (as shown in Fig. 1). This fact was addressed in [31] where the authors studied the temperature evolution of a TiNi alloy during dynamic loading. Among other things, they suggested that higher strain rates bring the stress-induced direct martensitic transformation conditions closer to adiabatic conditions. This phenomenon gives rise to peculiarities shown in Fig. 5.

Quasi-static loading in the mixed phase state at 63 °C (Fig. 5(a)) and in the premartensitic state at 87 °C (Fig. 5(b)) is followed by the usual behavior - the martensite stabilization effect is observed (recall that these test temperatures were reached by cooling from the high-temperature state). The bigger the residual strain, the stronger the stabilization effect. However, the higher the test temperature is from the martensitic state, the weaker is the stabilization effect, which is fully consistent with results in [24,26] and the damaged boundary hypothesis described above. In this case, the martensite boundaries are less damaged, compared to active deformation in the martensitic state. The martensite appears and grows oriented in the same direction as the load, exhibiting so-called transformation plasticity effect. Active deformation in the martensitic state has a more "aggressive" influence on the martensite boundaries, compared to transformation plasticity effect.

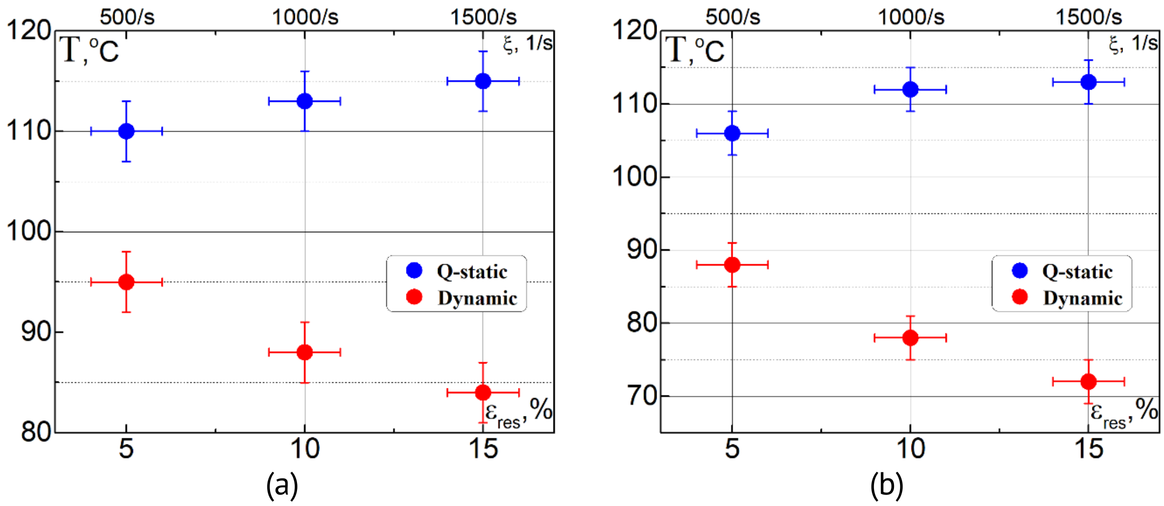

Fig. 5. The values of As in the first heating after tests at 63°C (a) and 87°C(b) depend on the strain rate ξ and the residual strain ε_{res} (● – after quasistatic deformation; ● – after high strain rate loading)

MSE is not observed after high strain rate loading. The temperature of the reverse martensitic transformation A_s during the first heating does not increase despite the growing residual strain. This feature can be explained by a combination of the both hypotheses mentioned above [26,31]. If higher strain rates bring the conditions of stress-induced martensitic transformation closer to adiabatic conditions, the martensite formation does not occur under high strain rate loading (at least it is significantly less than in the quasistatic case). This is because the transformation heat does not have opportunity to be distributed and dissipated in the environment under adiabatic condition. Thus, the only way is to accumulate the strain in the austenitic phase rather than through martensite formation. If the martensite remains undeformed, its boundaries will not be damaged, and therefore the martensite stabilization effect cannot occur.

The martensite stabilization effect depends on the loading rate in martensitic, premartensitic, and mixed phase states. The results are consistent with the results of other authors and can be explained by hypotheses presented in the literature.

Conclusions

The loading rate has a significant impact on the properties of NiTi shape memory alloy, including the martensite stabilization effect. An increase in the loading rate in the martensitic state results in a higher stabilization effect. However, high strain rate loading in the premartensitic and mixed-phase states does not lead to martensite stabilization, unlike in the quasi-static case. This behavior is consistent with the results and the hypotheses of other authors. The hypothesis that the conditions of stress-induced martensite formation are close to adiabatic in the dynamic case, as well as the idea that martensite boundaries are damaged under load, can explain the features presented.

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