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Peculiarities of residual strain accumulation during thermal cycling of TiNi alloy

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ABSTRACT

Strain variation on thermal cycling of the TiNi alloy under a constant stress of 50 MPa through the temperature range of complete as well as incomplete forward martensitic transformation was studied. The thermal cycling of the alloy through the temperature range of incomplete forward martensitic transformation was carried out to realize 25%, 50% or 75% of temperature range of forward phase transition. The thermal cycling of the TiNi alloy through the temperature range of the complete forward martensitic transformation resulted in observation of "training effect" (an increase in values of transformation plasticity and shape memory effects strain) and accumulation in residual plastic strain. It was shown that observation of "training effect" as well as accumulation of residual strain depended on the completeness of the forward martensitic transformation. As higher the fraction of temperature range of forward martensitic transformations on thermal cycling as stronger variation in values of shape memory effects and higher the accumulated plastic strain on the thermal cycling of the TiNi alloy. These phenomena were due to that the martensite accommodation process was elastically in the early stage of forward martensitic transformation. The plastic accommodation of martensite took place on the final stage of forward phase transition.

1. Introduction

It is well-known that the properties of equiatomic TiNi alloys change during thermal cycling. It is shown in variation in the parameters of martensitic transformations (temperatures and sequence) during thermal cycling without stress [1–18] and observation of the "training effect" (an increase in the values of the transformation plasticity and the shape memory effects) on thermal cycling of TiNi alloys under a constant stress [3,5,19–26]. Both of these phenomena are due to the appearance of irreversible strain on thermal cycling of the TiNi alloys through the temperature range of martensitic transformations [5,20,27–33].

In the case of a TiNi alloy that is subjected to thermal cycling without stress through the temperature range of the martensitic transformation no macroscopic strain is observed. However, transformation from the austenite to the martensite phase is accompanied by a large shear strain on the microscopic level [34]. This phenomenon is due to growing martensite plates that create high local internal stress [25,31–33]. This stress may exceed yield stress in the local volumes of materials, leading to nucleation, multiplication and movement of dislocations [29–33]. These effects have been verified by the TEM and X-ray data demonstrating that defect density increases during thermal cycling of a TiNi alloy through the temperature range of martensitic transformations [11,13,25,26,29,35].

On cooling a TiNi alloy without external load through the temperature range of the martensitic transformation, the 24 crystallographic variants of martensite appear in each grain and a preferable place for strain accumulation does not exist. In the case of cooling TiNi alloys under constant stress, the martensite variants where a shear strain coincides with the direction of external forces appear and accumulation of macroscopic reversible strain (the transformation plasticity effect) is observed. Moreover, the formation of "oriented" crystals leads to the appearance of macroscopic irreversible strain in the sample [11,13,25,26,28,36]. Accumulation of residual strain results in the observation of some "negative" effects, such as a change in sample sizes, degradation in the characteristics of the martensitic transformations (a decrease in temperatures and change in sequence) and a decrease in fatigue life [14,22,24,28,37]. These phenomena prevent these materials from wide application due to requirement of the repeated adjustment of application conditions [38]. Hence, it is very important to find a way to control the residual irreversible strain accumulation during the thermal cycling of TiNi alloys. The aim of present study is to investigate this problem by examining the peculiarities of residual strain accumulation during the thermal cycling of a TiNi alloy under stress.

2. Materials and methods

TiNi alloy wire samples, with a diameter of $d = 0.5$ mm and a length of 40 mm, annealed at a temperature of 773 K for 1 h, were used. To study a martensitic transformation the samples were cooled and heated at a temperature range of 390–290 K in a differential scanning calorimeter (DSC) at a cooling/heating rate

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of 10 K/min. DSC results have shown that after heat treatment the alloy underwent martensitic transformation on cooling from the cubic B2 phase to the monoclinic B19′ phase at temperatures of M_s = 337 K, M_f = 328 K, and the reverse transformation B19′ → B2 on heating at temperatures of A_s = 357 K, A_f = 370 K.

Resistivity measurement [1,3,4,8,9,20] and thermal cycling under constant load [3,5,19–26] are common techniques applying for study of kinetics of martensitic transformations and functional properties of shape memory alloys during thermal cycling. In the present work to study the influence of thermal cycling on characteristics of the martensitic transformations and the functional properties of the TiNi alloy, the samples were subjected to thermal cycling under three different conditions:

- through the temperature range of the complete forward martensitic transformation without stress;
- through the temperature range of the complete forward martensitic transformation under a constant stress of 50 MPa;
- through the temperature range of the incomplete forward martensitic transformation under a constant stress of 50 MPa.

Thermal cycling of the sample under a constant stress of 50 MPa was carried out using a testing machine Lloyd 30 K Plus, equipped with a thermal chamber. The sample was heated up to a temperature of 390 K, at which point the alloy was in the austenite state, loaded up to 50 MPa at a constant temperature and subjected to thermal cycling under constant stress in the temperature range of the complete martensitic transformation from 390 to 300 K.

Thermal cycling of the sample under the constant stress of 50 MPa in the temperature range of the incomplete martensitic transformation was carried out according to the following scheme. The sample was heated up to 390 K, loaded up to a stress of 50 MPa, then cooled down to the one of temperatures T_1, T_2 or T_3, belonging to the temperature range of $M_s \div M_f$, and heated up to 390 K. Temperatures T_1, T_2 and T_3 were determined as $T_1 = M_s - \frac{3}{4}\Delta T$, $T_2 = M_s - \frac{1}{2}\Delta T$ and $T_3 = M_s - \frac{1}{4}\Delta T$, where, ΔT was the temperature interval of the transformation plasticity effect found during each thermal cycle through the temperature range of the complete forward martensitic transformation. Each sample was subjected to 30 thermal cycles in the temperature intervals of 390 K–T_1, 390 K–T_2 or 390 K–T_3 in order to study the influence of fraction of the temperature interval of the forward martensitic transformation on the stability of functional properties and residual strain accumulation in the TiNi alloys during thermal cycling.

Additionally, the influence of thermal cycling of the TiNi alloy on the temperatures and sequence of the martensitic transformation was studied by resistivity measurements. The resistivity of the sample was measured by 4-points method during thermal cycling of the sample without stress. Moreover, the resistivity of the sample was measured at a temperature of 77 K before and after thermal cycling in order to study the influence of thermal cycling on the resistivity increment ($\Delta\rho_{77K}$). As resistivity (ρ_{77K}) at a temperature of 77 K is generally determined by defect density thus, variation in the resistivity increment ($\Delta\rho_{77K}$) may indicate variation in defect density in the sample.

3. Experimental results

3.1. Thermal cycling of the TiNi alloy through the temperature range of the complete forward martensitic transformation without stress

To study the influence of thermal cycling of the TiNi alloy on martensitic transformations the sample was subjected to 100 thermal cycles without stress. Fig. 1 shows the dependences of resistivity on temperature, obtained on cooling and heating the TiNi alloys in the temperature range of 390–300 K. It is seen that in the 1st cycle the resistivity sharply decreased on cooling from 330 to 320 K and sharply increased on heating from 354 to 361 K. Such resistivity behavior was due to the forward martensitic transformation from the cubic B2 phase to the monoclinic B19′ phase on cooling, and the reverse martensitic transformation from the B19′ to the B2 phase on heating. Thermal cycling of the TiNi alloy through the temperature range of martensitic transformations resulted in variation in resistivity vs temperature curves. Starting in the 3rd cycle, an increase in resistivity on cooling was observed before a decrease in resistivity. An increase in resistivity may be due to only the transformation from the cubic B2 phase to the rhombohedral R phase. Hence, one may conclude that the kinetics of martensitic transformation had changed and thermal cycling led to variation in sequence of forward martensitic transformation from B2 B19’ to B2 → R → B19’. Moreover, the temperature of martensitic transformation decreased from cycle to cycle. The results obtained have shown that the resistivity vs temperature curve became stable from the 30th thermal cycle (Fig. 1).

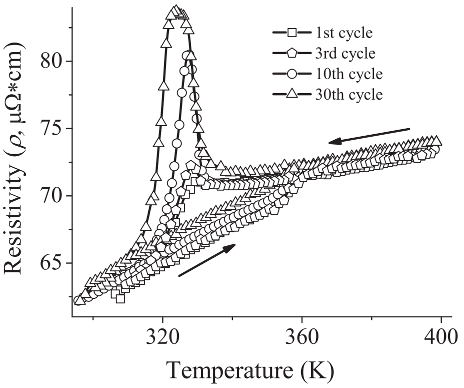

Fig. 1. Resistivity vs temperature curves obtained in the 1st, 3rd, 10th and 30th thermal cycle in TiNi alloy.

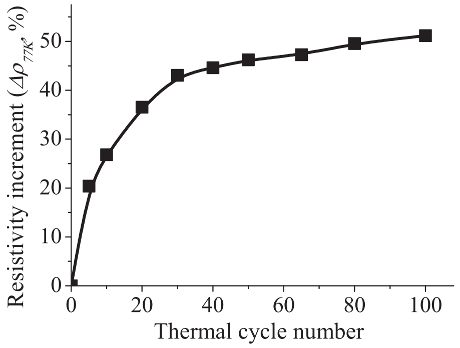

Fig. 2. Dependence of resistivity increment $\Delta\rho_{77}$ measured at a temperature of 77 K, on thermal cycle number in TiNi alloy subjected to thermal cycling without stress.

Fig. 2 demonstrates the dependence of the resistivity increment found as a difference between the resistivity measured at 77 K before the 1st cycle and after cycling, on the thermal cycle number. One may see that resistivity strongly increased during the first 30 thermal cycles, followed by a decrease in the rate of $d\Delta\rho/dN$. However, saturation in resistivity was not observed even in the 100th thermal cycle.

3.2. Thermal cycling of the sample under a constant stress of 50 MPa in the temperature range of complete forward martensitic transformation

Strain vs temperature curves were obtained on thermal cycling of the TiNi alloy under a constant stress of 50 MPa through the temperature range of the complete martensitic transformations. Values of the transformation plasticity effect ε^{TP} the shape memory effect ε^{SM} and irreversible strain ε_{ir} were determined for each thermal cycle, as shown in Fig. 3. The dependences of values of the transformation plasticity and the shape memory effects on the thermal cycle number are presented in Fig. 4. It is seen that as the number of cycles increases the values of the transformation plasticity and the shape memory effects increases significantly hence, one may conclude the “training effect” was found during thermal cycling. The main variation in values of shape memory effects was observed in the first 15 cycles. Starting in the 15th thermal cycle the values of the shape memory effects had slightly changed during subsequent thermal cycling. So, the value of the transformation plasticity effect rose from 0.8% to 2.2% during cy-