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Deformation of Ti–51.5 at.%Ni alloy during thermal cycling under different thermal-mechanical conditions

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ABSTRACT

One of the difficulties for application of TiNi shape memory alloys in actuators and the heat engine is an accumulation of a residual strain during thermal cycling. This problem may be solved by using a TiNi alloys with high yield stress or development of a special way for working cycle. The aim of the present work is a study of deformation behaviour and work performance in Ti–51.5 at.%Ni alloy during thermal cycling under different thermal-mechanical conditions. The samples were subjected to 30 thermal cycles through the temperature range of martensitic transformations under three different ways in torsion. The first sample was cooled and heated under a constant stress of 50 MPa, the second sample was cooled under the stress of 50 MPa and heated under the stress of 200 MPa (asymmetrical cycle). The third sample was cooled under the stress of 50 MPa, heated under the stress of 200 MPa, then unloaded and loaded in an opposite direction up to stress of −50 MPa, cooled down and heated under the stress of −200 MPa (symmetrical cycle). The results showed that the accumulation of a residual strain was found in all studied samples. However, thermal cycling under a symmetrical cycle resulted in the smallest accumulation of the strain in the sample.

1. Introduction

Shape memory alloys undergoing the thermal elastic martensitic transformation attract the attention of scientists due to the demonstration of unusual mechanical behaviour such as rubber-like deformation (pseudoelasticity effect), accumulation of strain on cooling under constant stress (transformation plasticity effect), strain recovery (the shape memory effect), spontaneous strain variation on cooling and heating (the two way shape memory effect) and generation of stress (stress recovery effect) [1]. Such behaviour allows the use of these alloys for many technical and medical applications [2–7]. One possible application is that of a heat engine transforming heat energy into mechanical or electrical energy [8–11]. This type of engine becomes sought especially after the bad anthropogenic impact on the environment because the martensite heat engine can produce energy without environmental pollution or fuel exhaustion.

The possibility of shape memory alloys for work production based on the ability of preliminary deformed alloys for strain recovery under a counteracting force [1,12]. To increase the positive balance of work in the work performance cycle of the heat engine it is necessary to decrease the work expended on the preliminary deformation, and to increase the work produced on strain recovery on heating. To achieve this, use of the following cycle was suggested in [13]. The sample was cooled down through a temperature range of the forward martensitic transformation under a constant stress, hence the deformation of the sample was realised by the transformation plasticity effect. Heating of the deformed sample through the temperature range of the reverse martensitic transformation was carried out under constant stress, which was higher than the stress acting on cooling. Its scheme allowed for producing effective work of approximately 10 MJ/m^3 in TiNiCu alloys. However, it was found that during the thermal cycling of the sample under the condition of work production, a large residual strain accumulated in the sample. So, 30 thermal cycles under cooling conditions of 50 MPa and heating of 300 MPa by torsion, resulted in a 120% accumulation of residual plastic strain. Accumulation of residual strain influences the parameters of the heat engine in a negative manner, due to the variation in working body characteristics, such as the geometric sizes and temperature kinetics of the martensitic transformations, which requires the adjustment of the heat engine design.

Plastic strain accumulates in the sample because the strain recovery on heating is not perfect and irreversible strain takes place in each thermal cycle even if the stress acting on cooling is equal to the stress acting on heating. To avoid the unilateral accumulation of plastic strain it is necessary to compensate for the irreversible

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strain that appears in each work performance cycle. This may be achieved if the stress applied to the sample for each number of even cycles will act in the opposite direction to the odd cycles. In this case the irreversible strain has to accumulate in the opposite direction in each cycle, and the total residual plastic strain accumulation must be less than in the cycle described in [13]. The goal of the present work is to study the deformation behaviour and work performance during thermal cycling under different conditions of work production.

2. Experimental

Cylindrical samples of the Ti–51.5 at.%Ni alloy with a diameter of 4 mm and a length of 30 mm were used. The samples of Ti–51.5 at.%Ni were quenched from 1070 K in water and then annealed at 770 K for 5 h and at 723 K for 3 h. The DSC experiments showed that after preliminary heat treatment the studied alloy underwent B2 → R → B19′ martensitic transformations (from the cubic phase to the monoclinic phase through the rhombohedral phase) on cooling (R_s = 298 K, R_f = 283 K, M_s = 270 K, M_f = 238 K) and B19′ → B2 reverse transformation on heating (A_s = 295 K, A_f = 317 K).

A mechanical test was carried out in the torsion mode and values of stress and strain were measured in the sample's outer fibres at the suggestion of ideal plasticity. In the present study three schemes of experiments were chosen.

The first scheme of experiments was the same as in [13]. The sample was cooled under low stress and heated under a high stress to produce effective work. Firstly, the sample was elastically loaded up to a stress of 50 MPa at constant temperature, then cooled to a temperature of 220 K. At a temperature of 220 K the stress was increased to 200 MPa, and then the sample was heated under constant stress. At a temperature of 400 K the sample was unloaded to a stress of 50 MPa and then the procedure described was repeated.

The second experimental scheme differed from the first in that the stress acting on cooling and heating in each even cycle was applied in the opposite direction to the odd cycle. In the odd cycle, the sample was elastically loaded up to a stress of 50 MPa at constant temperature, then cooled to a temperature of 220 K. At a temperature of 220 K the stress was increased to 200 MPa, and then the sample was heated under a constant stress. At a temperature of 400 K the sample was unloaded to a stress of 50 MPa and unloaded down to zero stress. After that, in the even cycle the sample was loaded to −50 MPa (in the opposite direction), cooled to a temperature of 220 K, and at this temperature of 220 K the stress was increased to −200 MPa and the sample was heated to a temperature of 400 K, then the sample was unloaded to −50 MPa and then again down to zero stress. Following this the described procedure was repeated. Odd and even cycles in the second procedure may be considered as one "symmetric" cycle. Hence, the cycle described in the first scheme may be considered as an "asymmetric" cycle.

Additionally, the sample was cooled and heated under constant stress to study the strain variation during thermal cycling without work performance. The sample was loaded at a temperature of 400 K and then subjected to thermal cycles from 400 K to 220 K under a constant stress of 50 MPa. This cycle may be considered a "constant stress" cycle.

In the present study the 30 "asymmetric", "symmetric" and "constant stress" cycles were carried out. In each thermal cycle the values of transformation plasticity effect strain γ^{TP}, shape memory effect strain γ^{SM}, irreversible strain γ_{ir} were found as shown in Fig. 1a and the work output A was found as shown in Fig. 1b. It is seen that the value of transformation plasticity effect strain γ^{TP} was determined as a strain accumulated on cooling the sample under constant stress through the temperature range of the forward martensitic transformations; the value of shape memory effect strain γ^{SM} was determined as a strain recovered on heating the sample under constant stress though the temperature range of the reverse martensitic transformation; the value of irreversible strain γ_{ir} was determined as a strain found in the sample under unloading of the sample down to zero stress at a temperature of 400 K. As an irreversible strain was found in the each thermal cycle hence, it resulted in accumulation of residual plastic strain γ_r from cycle to cycle. The value of residual plastic strain was found as a sum of irreversible strains found in each thermal cycles. The value of work output was estimated as in [13]. To estimate the work output the strain vs temperature curves were plotted in the stress vs strain coordinates (see Fig. 1b). As the work output is equal to difference between the work expended on the deformation of the sample during loading in austenite state at a temperature of 400 K (segment 0–a), cooling under a constant stress through the temperature range of the forward martensitic transformation (segment a–b) and loading in martensite state at a temperature of 220 K (segment b–c), and work produced on strain recovery on heating under a constant stress through the temperature range of reverse martensitic transformation (segment c–d) and unloading in austenite state at a temperature of 400 K (segment d–e). Thus, effective work *A* in each ("asymmetric" or "symmetric") thermal cycle may be estimated as a square within the figure e–b–c–d–e in stress τ–strain γ coordinates (Fig. 1b). So, the chosen experimental procedure allowed the influence of thermal cycling on values of strains of γ^{TP}, γ^{SM}, and γ_r and work output *A* to be studied in different conditions of work performance.

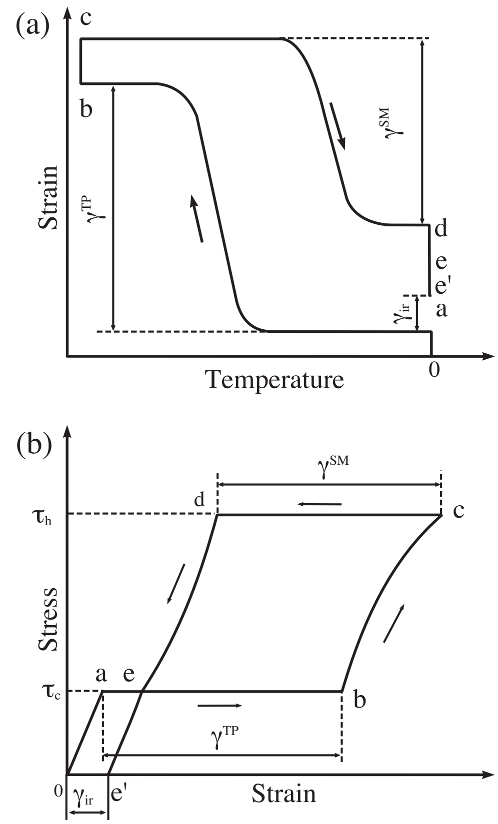

Fig. 1. The scheme of the estimation of strains of γ^{TP}, γ^{SM}, and γ_{ir} in strain vs temperature coordinates (a) and work output A in stress–strain coordinates (b).

3. Results and discussion

Fig. 2 shows the strain vs temperature curves obtained on cooling and heating the TiNi alloy under the different schemes. It is seen that on cooling and heating under a constant stress of 50 MPa (Fig. 2a) the strain accumulates due to the transformation plasticity effect and it recovers due to the shape memory effect and a hardly detectable irreversible strain is found.

Fig. 2b demonstrates the strain vs temperature curves obtained in the "asymmetric" cycle. Strain accumulation on cooling occurs in the same manner as in Fig. 2a because the stress acting on cooling is equal to 50 MPa. At a temperature of 220 K the alloy is in a martensite state so, an increase in stress from 50 MPa to 200 MPa results in the deformation of the alloy by the martensite reorientation mechanism, which leads to strain accumulation of 1.22% to 4.76%. This strain is reversible and can be recovered on heating. However, the data have shown that partial strain recovery observed on heating under a stress of 200 MPa and an irreversible strain of 0.27% appears in the sample after the first thermal cycle.

Fig. 2c demonstrates the strain vs temperature curve obtained in "symmetric" cycle. It is seen that the "symmetric" cycle consists of two "asymmetric" cycles where the stress is applied in opposite directions. During the positive half of the "symmetric" cycle where the stress is applied in the positive direction, the value of irreversible strain is 0.2%, however, during the negative half of the "symmetric" cycle the value of irreversible strain is −0.58%. As the values of irreversible strain accumulated in the opposite directions are added, the total value of irreversible strain for the complete "symmetric" cycle is −0.38%.

Fig. 3 shows the dependences of the transformation plasticity and shape memory effect's values on the number of thermal cycles under the different schemes. It is seen that values of deformation