FEATURES OF SHAPE CHANGE OF RING-SHAPED FORCE ELEMENTS MADE OF TiNi ALLOY AFTER ACTIVE DEFORMATION

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ABSTRACT

The paper considers the features of shape change of ring-shaped force elements made of TiNi alloy during thermocycling. Non-monotonic deformation characteristics were obtained. The decrease in the sample shape during thermocycling is associated with incomplete martensitic transformation of the material due to temperature shifts during training. Holding of the sample in the martensitic state can lead to stabilization of the martensitic transformations' temperatures and an increase in the proportion of martensite in the ring material. It can increase the shape change of the ring.

Keywords: shape memory alloys, two-way shape memory effect, TiNi, ring-shaped force elements.

INTRODUCTION

Shape memory alloys have several unique physical and mechanical properties, such as: shape memory effect (SME), two-way shape memory effect, super elasticity, force generation, direct transformation plasticity, reduction in elastic modulus, increase in internal friction during phase transformation and others. The ability of a material to return to its pre-deformed shape after a change in temperature is called the shape memory effect. The ability of a material to change its shape on subsequent cooling in the direction of the load applied during pre-deformation and heating is called the two-way shape memory effect. The functional capabilities of shape memory materials can be used in various fields of engineering (from medical to aerospace) [1 - 5].

The range of materials being studied is expanding. Researchers are evaluating the influence of alloy additives, manufacturing methods and heat treatment on functional properties [6 - 10]. It is important to note the influence of deformation methods and the shape of the force elements on the physical and mechanical properties, as these factors can significantly affect the material properties [11, 12].

The beginning of a comprehensive study of two-way shape memory in metals with thermoelastic martensitic transformations dates to the mid-1970s of the last century. For two decades, a large amount of data was obtained on the shape change regularities of samples of alloys based on Ti-Ni, Fe-Ni, Cu-Zn-Al, Fe-Pt, Cu-Mn and several other materials. Against the background of the strain-force characteristics of the shape memory effect, the similar parameters of two-way shape memory were much smaller. To improve the strain-force characteristics of two-way shape memory, the technique of repeated thermal cycling under load is used [13]. Another way of improving the two-way effect is used in [14, 15]. Experiments have been carried out on Cu-Zn-Al, Ni-Fe-Ga-Co alloys and some variants of titanium nickelide. A sample is plastically deformed in the martensitic or austenitic state. After unloading, the material is heated or cooled to a different phase state. The sample is then returned to its original temperature. The whole process is repeated many times.

The realisation of two-way shape memory in ring-shaped force elements made of titanium nickelide is shown in [11, 16 - 18]. In the first series of experimental studies, multiple thermocycling with cooling under load and heating in the free state was used [11, 16]. In the second series of experiments, the ring-shaped elements were thermocycled under load and additionally loaded by active deformation in the martensitic state before each subsequent heating cycle [17, 18].

This paper presents the features of the shape change of ring-shaped force elements during thermal cycling with loading in the martensitic state and heating in the free state.

EXPERIMENTAL

A ring of Ti - 50.5 at. % Ni alloy wire with a diameter 62.5 mm was used as a sample (Fig. 1). The geometry of the specimen corresponds to the characteristics of the force elements of miniature presses acting on the shape memory effect [4]. The cross-sectional diameter of the wire was 2 mm. The sample was shaped by annealing at 500°C for 30 min with cooling in air.

The characteristic temperatures of the martensitic transformations in the TiNi alloy were determined after quenching using a differential scanning calorimeter. Sample of 47.5 mg mass were cooled and heated in the temperature range from 140°C to - 100°C at a rate of 10 K min^{-1} in a Mettler Toledo 822 calorimeter chamber. The temperatures of the beginning and the end of the direct martensitic transformation in the quenched alloy were M_s = 21°C, M_f = 6°C, respectively, the reverse transformation took place in the temperature range from A_s = 35°C to A_f = 49°C (Fig. 2). To stabilize the temperature range of the martensitic transformations, five preparatory technological thermocycles were carried out, in which the sample material was transferred from the martensitic state and back to the austenitic state.

The sample was deformed using an elastic spring in the martensitic state at - 14°C with a force F_0 = 34.5 N (position 2 in Fig. 3). The initial force F_0 was

Fig. 1. Ring-shaped force element made from Ti - 50.5 at. % Ni alloy.

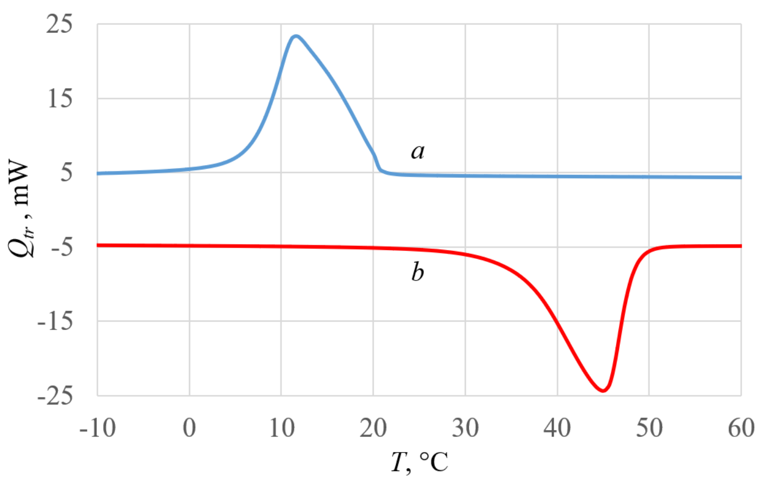

Fig. 2. Calorimetric curves obtained during cooling (a) and heating (b) of Ti-50.5 at. % Ni alloy samples, subjected to quenching.

chosen according to the load-unload curve of the ring element in the martensitic state shown in Fig. 4. The second stage of deformation of the ring element begins when the force equal to F_0 is reached. At the end of the deformation process (position 3 in Fig. 3), the active load was removed and a partial return to the ring shape was observed (position 4 in Fig. 3) due to elastic deformation. The ring-shaped force element was then heated in the free state to a temperature of 140°C (position 5 in Fig. 3). As a result of the heating, the sample completely returned to its original shape. The sample was cooled to below -14°C, at which point the shape changes associated with the direct transformation plasticity caused by residual stresses (position 6 in Fig. 3). Then cycles 2 - 6 were repeated (Fig. 3). The change in diameter of the ring-shaped sample along which the load was applied was monitored.

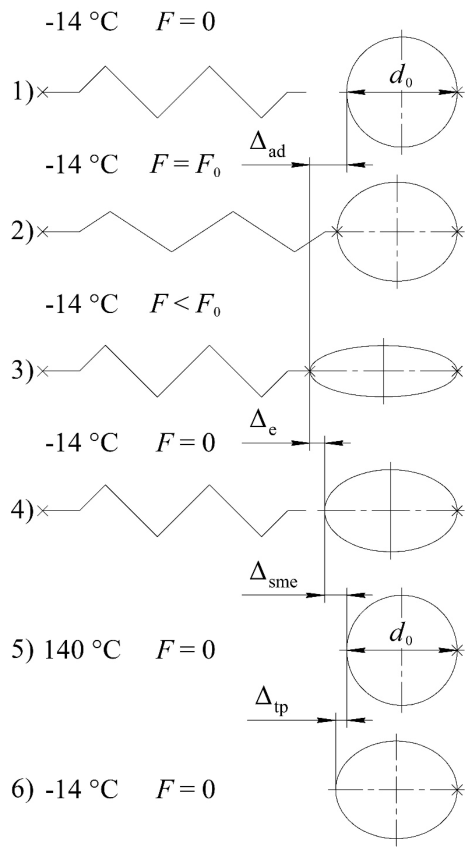

Fig. 3. Scheme of the training of ring-shaped force element: 1 - before loading, 2 - at the moment of loading in martensitic state, 3 - after active deformation in martensitic state, 4 - after removal of external load, 5 - after heating in free state, 6 - shape change of the direct transformation plasticity accumulated during the cooling process due to internal residual stresses, d_0 - initial size, Δ_e - shape change after removal of external load, Δ_{sme} - shape change during heating, Δ_{tp} - shape change during cooling.

RESULTS AND DISCUSSION

The possibility of increasing the two-way shape memory effect of a ring-shaped force element to values comparable to those of the SME is shown in [11]. The training with cooling under load was carried out in more than 60 training cycles to obtain the maximum two-way shape memory values. The strain of the two-way shape memory effect depends on the deformation during the cooling process. The shape change during cooling is associated with the direct transformation plasticity effect of under the action of internal residual stresses resulting from incompatibility of deformations. The shape changes of the ring before heating consisted of two components of deformation due to direct transformation plasticity accumulated during the cooling process and active deformation.

Fig. 5 shows the shape change of the ring in the first cycle in which the form change directed against the SME Δ_{tp} was not observed. In the martensitic state, the ring-shaped force element was deformed by an elastic spring for 12.1 mm (position 1 in Fig. 5). After removal of the active load the diameter of the deformed oval decreased by 4.5 mm (position 1 in Fig. 5). The active deformation processes during heating took place at temperatures in the furnace ranging from ~ 54°C to 79°C. As a result of the heating and SME processes the shape of the sample returned by 6.9 mm.

After 10 thermal cycles the ring shape change during cooling Δ_{tp} increased from zero value in the first thermal cycle to a value of 4 mm (Fig. 6). Thereafter, both an increase and a decrease of the characteristic Δ_{tp} were observed during further thermocycling. The maximum Δ_{tp} value of 4.8 was observed at cycle 18. Thereafter, the values decreased to 4.1 mm during two cycles.

The growth of the ring shape change reached 10 mm by cycle 20 and continued when the transformation plasticity was used to train TWSME [11]. The two-way shape memory characteristics had not decreased during thermocycling in the control cycles. Stabilization of the

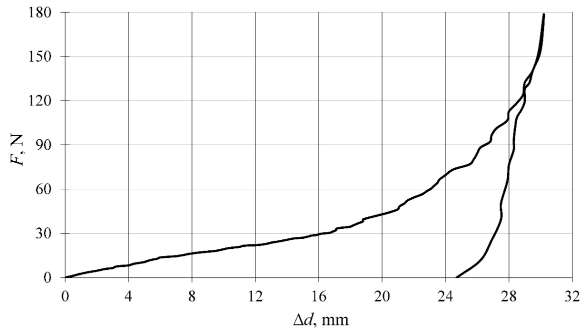

Fig. 4. Dependence of the deformation Δd on the applied load F and subsequent unloading of the ring-shaped force element.

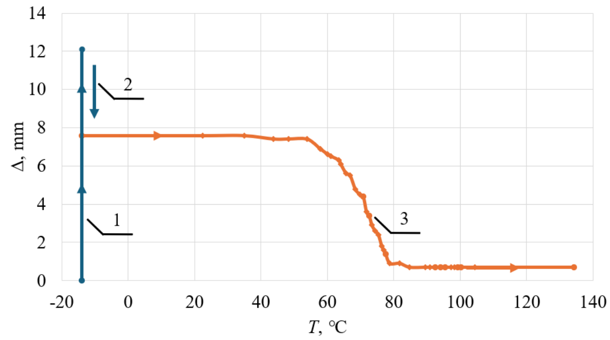

Fig. 5. Temperature dependence of ring shape change Δ in the first cycle: 1 - active shape change in the martensitic state, 2 - return of the elastic component of deformation, 3 - shape change due to SME during heating.

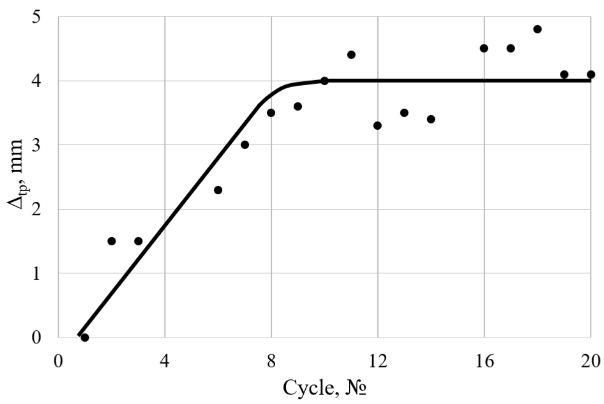

Fig. 6. Shape changes Δ_{tp} of a ring-shaped sample during thermal cycling.

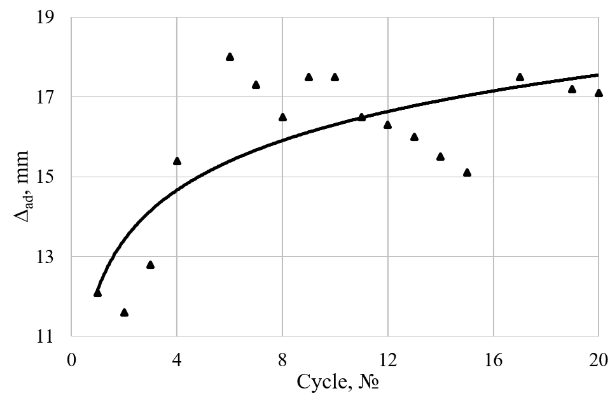

Fig. 7. Shape change Δ_{ad} of the ring-shaped sample after active deformation during thermocycling.

two-way shape memory strain occurred after about 60 cycles of training. The maximum Δ_{tp} of 12.5 mm had been approached. The growth of Δ_{tp} during active deformation of rings with similar geometry did not reach 5 mm after 20 training cycles. The force applied to the samples was 1.5 times higher than in the experiments in [11].

Fig. 7 shows the value of Δ_{ad}, which represents the shape change of the ring-shaped sample due to active deformation in the martensitic state. The non-monotonicity of the observed values Δ_{ad} is noted. The decrease in strain characteristics is probably due to the incompleteness of the martensitic transformation. A significant decrease in the end temperature of direct martensitic M_f is possible up to the training of two-way shape memory with load application and thermocycling. Such a temperature decrease during thermocycling can reach about 50°C [13]. The temperature difference between the M_f in the hardened TiNi alloy and the cold chamber temperature was ~ 20°C.

Non-monotonicity of the deformation characteristics of ring-shaped force elements during cooling has been observed in [16]. There is an increase in the temperature of direct martensitic transformation during holding in the martensitic state in TiNi alloys [19]. This allows a larger volume of material in the ring-shaped force elements to transform from austenite to martensite, giving a slight increase in deformation properties.

CONCLUSIONS

The obtained results demonstrate the non-monotonicity of the shape changes in ring-shaped force elements made of titanium nickelide during cooling after active deformation. At the same time, the shape changes during cooling are practically 3 times lower than the similar values obtained by training using the transformation plasticity effect. This fact allows us to choose a preferred method of two-way shape memory training for using this property of alloys with thermoelastic martensitic transformations in technical applications.

The non-monotonicity of the deformation characteristics during thermocycling indicates the need to control the temperatures interval of the direct martensitic transformation to achieve a fulled shape change of the ring-shaped force elements during cooling.

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Authors' contributions*: Conceptualization, E.K., E.O.: methodology, E.K., A.T.: investigation, A.M., T.N., M.S.: data curation, T.L., E.K.: writing - original draft preparation, E.K.: writing - review and editing, E.K., E.O.*

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