The influence of the thermomechanical conditions and the geometric parameters of TiNi alloy force elements on the deformation processes of two-way memory effects

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Abstract. The paper presents data of the two-way memory effect deformation processes dependencies of the various TiNi force elements from different temperature and force modes.

1. Introduction
Studies of metallic materials with shape memory effect (SME) have shown the possibility of controlling their deformation properties due to thermal cycling with partial transfer of material from the austenitic to martensitic state and vice versa [1]. This was used to improve the operation of ring force beam elements (RFBE) in small-sized SheR presses [2]. Obtaining the first ring welded structures allowed the use of ovals as power elements not only in the mode of the SME, but also in the mode of reversible shape memory (RSM) [3]. In this connection, there is interest in regulating the deformation-strength properties of welded rings operating in the (RSM) mode, due to incomplete martensitic transformation. For wave-shaped power elements, the form-changing of reversible shape memory with complete phase transitions was investigated.

2. Results and discussion
First of all, we studied the thermal cycling of ring elements from temperature $M_m$ to $A_{sup}$ and back, where $M_s \leq M_m \leq M_f$, $A_{sup} > A_f$ ($M_s$ and $M_f$ are the temperatures of the beginning and end of the direct martensitic transformation, respectively, $A_f$ is the temperature of the end of the reverse phase transition).
Figure 1. Scheme of increasing the reversible memory of the RFE form: 1 RFE – before loading, 2 – RFE at the time of loading in the austenitic state, 3 – RFE after deformation of the direct transformation plasticity, 4 – implementation of the reversible memory of the RFE form, \(d_1\) – the initial size of the RFE, \(d_2\) – the size of RFE during deformation of plasticity of transformation, \(d(t)\) – RFE size during deformation of RSM.

The deformation of the sample under the conditions of plasticity of the transformation was performed using a coil spring (figure 1). Welded rings with a diameter of ~ 62 mm were made of TiNi alloy. Cooling occurred under isothermal conditions at temperatures of 270 K refrigerating chambers – within the interval \([M_s; M_f]\), 255 K – below \(M_f\) (Figure 1, position 3). Heating RFE was carried out without load in the thermostat. The temperature in the chamber was 430 K (above \(A_f\)) (figure 1, position 4). When heated, the original form was restored completely. At the next stage of heating, the cooling of the RSM was \(\Delta_{TWME} = d(t) - d_1\) (figure 1, position 4). After the first thermal cycle described, several preparatory process heat cycles were made. At the stage of lowering the temperature, the sample was under load, and during heating the SME developed in the free ring. Then, observations of the deformation process of the reversible shape memory were repeated. Three rings with different levels of the initial value of the training effort in each cycle: 8.2 H, 18.8 H, 32.7 H were tested.
Figure 2. Cyclic change in the value of the reversible shape memory during preparation with a force F: 1 – 8.2 Н, 2 – 18.8 Н, 3 – 32.7 Н and a minimum temperature of the thermal cycle 270 K.

Figure 3. Cyclic change in the value of the reversible shape memory when preparing with a force F: 1 – 8.2 Н, 2 – 18.8 Н, 3 – 32.7 Н and the minimum temperature of the thermal cycle is 255 K.

Figures 2 and 3 show how during the RSM under the specified temperature variation regimes the size of the rings along the loading line changed during thermal cycling. In the works [3, 4], the authors noted an increase in the reversible shape memory in nickel-titanium products during thermal cycling in the full transformation mode, it is also confirmed by the curves in figure 3. At an effort of $F = 8.2$ Н, a nearly linear increase in the RSM values was observed for 28 cycles. An increase in the force effect to 18.8 Н led to the $\Delta_{TWME}$ saturation, starting from the 10th cycle. And with a load of 32.7 Н, the characteristics of the shape change practically coincided with the corresponding process values at
$F = 18.8 \text{ H}$. In the case shown in figure 2, when the plasticity deformation of the transformation during thermal cycling developed in the range with a lower temperature limit within the interval of the direct phase transition, the growth of the reversible shape memory in all cases, stopped after reaching a certain value. Then there was a decline in the values of the deformation characteristics of the RSM. Further thermal cycling of the ring-shaped power elements resulted in a non-monotonic change in $\Delta_{TWME}$ at the cooling stage.

**Figure 4.** Cyclic change in the strain of plasticity of the direct transformation during preparation with a force $F$: 1 – $8.2 \text{ H}$, 2 – $18.8 \text{ H}$, 3 – $32.7 \text{ H}$; and minimum temperature of the thermal cycle 270 K.

**Figure 5.** Cyclic change in the strain of plasticity of the direct transformation during preparation with a force $F$: 1 – $8.2 \text{ H}$, 2 – $18.8 \text{ H}$, 3 – $32.7 \text{ H}$ and the minimum temperature of the thermal cycle is 255 K.
The pattern of shape changes in annular force elements caused by deformations of the plasticity of the transformation during thermal cycling $\Delta TP = d_2 - d_1$ is shown with the curves in figures 4 and 5. It should be noted that the reversals of the reversible shape memory (figure 4) occurred with the growth of the shape changes of ovals due to the plasticity of the direct transformation.

After 16 thermal cycle the sample which was under load of 32.7 H collapsed in the welding zone, being in the austenitic state. Since the second research program was carried out on this power element, the total operating time of the ring before failure was 73 triggers. This result requires an improvement in the technology of welding nickel-titanium rings.

![Figure 6](image)

**Figure 6.** Extension pattern of reversible shape memory in power elements of the “wave” type 8: 1,2 – thermal cycling in the free state with the initial linear dimension $d_1$, 3 – before loading along the line 9 with dimension $d_1(i)$, 4 – active sample deformation with the resulting size $d_2$, 5 – unloading the sample with obtaining the size $d_3$, 6 – implementing the shape memory effect with forming dimension $d_4$, 7 – implementing the reversible shape memory $d_5$, 10 – grabbing the deformation machine with a strain gauge, 11 – moving grip, $i$ – cycle.

As an alternative to spiral drives [5], capable of changing the characteristic size by 130% (helix height), a wave-like structure was investigated (figure 6). To study the characteristics of the reversible
shape memory, the shape change scheme was chosen, shown in figure 6. The power elements with five repetitive S-shaped links with a total length of 94 mm were made of a 2.5 mm diameter TiNi alloy wire. For the selected alloy, the characteristic temperature is $A_s = 350 \, K$, $A_f = 370 \, K$, $M_s = 310 \, K$ and $M_f = 280 \, K$, where $A_s$ is the onset temperature of the reverse martensitic transformation. The active deformation of the sample along the loading line 9 was carried out using the test setup described in [6] (the process is shown in figure 6). After the shape changing the sample was unloaded. As a result, a new form was acquired, due to plastic deformation of the material of the structure (5, figure 6). Then it was heated in a thermostat (6, figure 6). A temperature of ~ 430 K (above $A_f$) was maintained in his chamber. The reverse transfer of the actuator material was carried out in a refrigerating chamber at a temperature of 270 K (7, figure 6). At this stage of the experiment, the value of the RSM $\Delta_{TWME} = d_5 - d_4$ was monitored. After the completion of the specified cycle of thermomechanical processing, the sample with the characteristic size $d_5$ was subjected to the next loading. Then technological operations of unloading, heating and cooling were repeated.

Figure 7 shows the interdependence of the force effect on the wave-like structure and its deformation under loading up to 70 H.

![Figure 7](image_url)

**Figure 7.** Dependence of the shape changes $\Delta$ on the applied load $F$ and the subsequent unloading of the power element of the “wave” type, obtained on the deformation machine DTV.

Curve 1 in figure 8 shows the increase in the characteristic of the shape changing of the power element $\Delta = d_5 - d_i(i)$ from cycle to cycle. On the x-axis it is indicated the value of the maximum force $F$ of the corresponding stage of loading. The first loading of a wavy structure with a force of 70 H caused an increase in $\Delta$ to 10 mm. Deformations of reversible shape memory under these conditions were not found. An increase in the force effect to 80 H led to an increase in the characteristic size of the “wave” to 20 mm. The magnitude of the displacements due to the reversible shape memory was 2 mm. A further increase in the deforming force led to an almost linear increase in the characteristic parameter $d_2$ and $\Delta_{TWME}$. Thermomechanical processing of the sample according to the scheme shown in figure 6 allowed to get the movement of the wave-shaped power element in the RSM mode 19 mm by the 7th cycle. After obtaining this level of deformation parameters, the sample was transferred from the martensitic state to the austenitic state and back 10 times without load. At the same time, no degradation of the characteristics of the reversible shape memory was found. The temperature dependence of shape changing RSM $\Delta_{TWME}$ is shown in figure 9.
3. Conclusion

Thus, the obtained results and the data [3] indicate the need to ensure the completeness of the direct martensitic transformation to achieve controlled shape changing of the power elements at the expense of the RSM in process plants. The required level of movement of the reversible shape memory can be obtained by choosing the level of power effects. The experiments have also shown the need to improve the quality of welded joints.

To ensure a high level of reversible shape memory changes in technological processes, it is advisable to use wave power elements.
References

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