The influence of the temperature conversion rate on the deformation processes of the shape memory effect and transformation plasticity

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Abstract. The influence of the temperature conversion speed on the mechanical characteristics of metals with shape memory is mentioned in connection with the dissipative properties of this materials class. This paper presents the different cooling and heating regimes research results of ring-shaped force elements and spiral drives demonstrating the possibility of this parameter influence on their deformation characteristics in the temperature range of martensitic transformation.

1. Introduction
In the study of the shape memory effect (SME) and plasticity of transformation (PT), the development of which is due to thermoelastic martensitic transformations, until recently did not notice a significant effect on the deformation properties of the rate of temperature change [1]. However, in the process of developing drives for the multiple operation of technological devices operating in the mode of the SME and reversible shape memory (RSM), noticeable changes in the characteristics of the shape change due to the heating and cooling modes were found.

Investigation of the dependence of the deformation phenomena of the SME on the heating rate was carried out on spiral drives made of CuZn18Al7 wt.% (figure 1, a) [2] and ring-shaped force beam elements (RFBE) from an alloy of TiNi55.4 wt.% (figure 1, b) [3]. The diameter of the copper-zinc-aluminum alloy wire was 4 mm. RFBE was made of a two-millimeter wire. The height of the spiral of twelve turns was ~ 50 mm under the condition that the turns completely fit. The ring of the power element of titanium nickelide consisted of five turns and its outer diameter was ~ 63 mm. Samples of CuZnAl drives were annealed at 1073 K for 30 min and then quenched in water. The outer diameter of the helix was ~ 20 mm. The drive from titanium nickelide was annealed for 20 min at ~ 800 K and quenched in water.
The dependence of the deformation effects of the plasticity of the transformation on the change in cooling modes was studied on an ring-shaped force element made of a TiNi55.4 wt.% alloy from a two-millimeter wire. The ring consisted of one coil and had the shape of an elongated oval. The sample was annealed at 773 K for 20 min. Then, it was subjected to a three-fold thermal cycling with the transfer of material from the fully martensitic state to the austenitic state and back.

2. Results and discussion

When the helix was heated, a change in its height and rotation of the upper turn relative to the base was observed. Figure 2, a shows the temperature dependence of the height of the spiral. When heated from room temperature to 315 K, the geometrical characteristics of the CuZnAl actuator did not change. In the range of temperatures from 315 K to 335 K, the height of the helix increased by ~130%, reaching 112 mm. Further, up to 400 K, the shape of the helix was stable. The distance between the coils reached ~6 mm. The cooling of the spiral led to a significant restoration of the original geometric dimensions. In the temperature range from 313 K to 298 K, the drive height decreased to ~63 mm. Such an evolution of height did not change when the heating regimes changed. A different situation with the spiral torsion when heated. The rotation of the upper turn relative to the base (figure 2, b) is reflected in two graphs. Curve 1 shows how the angle of torsion α changes when the helix was placed from room conditions (temperature ~296 K) in a thermostat heated to 400 K. Curve 2 reflects the rotational process at a heating rate of the helix ~1 K / min. If in the first case, all deformation processes take place in 6 minutes. At the same time, the swing of the turn was only 3°. In the second case, the development time of the rotational motion lasts ~25 minutes. The angle of rotation at the same time reached 7°.

The study of the dependence of RFBE on changing the heating rate was carried out on a special LIND dynamometer, the circuit of which is shown in figure 3. At room temperature, a pair of “metallic
muscles” was brought into force interaction with the counterbody. A steel spiral spring was chosen as the counterbody. The dynamometer was placed in a thermostat chamber. With an increase in temperature, the control point displacement $\Delta = d(0) - d(t)$ ($d(0)$ is the initial characteristic size of the RFBE and $d(t)$ is the characteristic size at the current time $t$) was monitored. Knowing the value of $\Delta$, one can determine the level of the generated force: $F(t) = F_0 + K_1 \cdot \Delta$ ($F_0$ is the strength of the initial interaction of RFBE with the counterbody, $K_1 = 100$ N / mm is the rigidity coefficient of the counterbody).

Figure 3. Loading RFBE in a LIND dynamometer:
1 – RFBE, 2 – counterbody, 3 – movable plate, 4 – regulating fixed plate, 5 - measuring system, $d(t)$ – characteristic size of RFBE.

The RFBE heating modes are represented by temperature change diagrams in Figure 4. The initial force interaction of the “metallic muscles” with the counterbody corresponded to $F_0 = 706$ N. As a result of LIND’s placement in the heated thermostat (curve 1, figure 4), the development of the shape memory effect occurs monotonously. Forming begins after 2 minutes from the moment of placement in the thermostat, and ends at 12 minutes.

Figure 4. The dependence of the thermostat temperature change (a) and the distance between moving LIND plates (b) on the time in the heated state at 1 – $T = 393$ K and at heating rates: 2 – 1 K / min, 3 – 0.83 K / min, 4 – 0.68 K / min.

If the dynamometer is heated with a thermostat (curves 2–4, figure 4, a), then we observe a deformation counter-flow, that is, the initial stage of shaping the RFBE is opposite to the direction of the SME. With an average rate of temperature change $T$ in the thermostat $\sim 1$ K / min (curve 2, figure 4, a) the maximum offset of the opposite flow of 1 mm was noted at 42 minutes (curve 2, figure 4, b). At the same time, the interaction force of RFBE with the counterbody decreased to 606 N. A decrease in heating rates to 0.83 K / min (curve 3, figure 4, a) increases the displacement to 2 mm (curve 3, figure 4, b). The maximum is marked at the sixtieth minute. The minimum value of the force acting on the RFBE was found to be 506 N. At a heating rate of 0.68 K / min (curve 4, figure 4, a), the maximum countercurrent was observed at 70 minutes (curve 4, figure 4, b). However, its value decreased to $\sim 1.67$ mm. And the smallest force of interaction of RFBE with a counterbody increased relative to the same parameter noted in the third experiment, and was $\sim 539$ N.
Deformation processes depending on the cooling rate were studied using a spring dynamometer (figure 5). The oval of the force element was heated in the unloaded position to 400 K. This temperature is sufficient for transferring the ring material to the austenitic state. Under these conditions, a sample with \( d_1 = 73 \) mm was brought into contact with a stretched spring with a force of \( F_0 = 6.4 \) N. Then, during the cooling process, the ring was changed to form (figure 6). The oval ring was pulled along the line of action of the load. The control point offset is represented for four cooling modes. When the sample cooled with a thermostat (curve 1, figure 6), the form change began at \( \sim 100 \) min at 320 K. This process lasted about 200 minutes to a temperature of 300 K. The ring cooling rate at this stage was \( \sim 0.1 \) K / min. The value of \( d_1 \) increased by \( \Delta = 7.3 \) mm, where \( \Delta = d(t) - d_1 \). Unlike heating, when \( d_1 \) decreases as a result of the SME, in this situation the magnitude of this geometric parameter increases. The force effect \( F(t) = F_0 - K_2 \cdot \Delta \) (\( K_2 = 0.6 \) N / mm) decreased to 2.2 N.

When the dynamometer is removed from the thermostat and cooled at room temperature of 299 K (curve 1, figure 6), the form change is observed from 8 to 60 minutes. The value of \( d_1 \) increased by 6.5 mm, and the force effect on the oval decreased to 2.75 N. At the same time, the average cooling rate in the range of direct martensitic transformation is 0.4 K / min.

When cooled in cold rooms with temperatures of 280 K (curve 3, figure 6) and 270 K (curve 4, figure 6), the change in the geometric parameters of the power element began at the 4th and 3rd minutes, respectively. In the third cooling mode, \( d_1 \) increased by 5 mm, and the force interaction with the spiral spring decreased to 3.4 N. During the fourth mode of lowering the temperature, the change in \( d_1 \) was only 3.5 mm, and \( F(t) = 4.4 \) N. The rates of temperature change were respectively 1.7 K / min and 2.9 K / min. In this case, \( t \) was equal to 10 minutes. Change of the form occurred in the minimum time interval. In all four experiments, the heating of the annular force elements led to a complete restoration of the original shape.

Figure 5. Load diagram of the power elements in the dynamometer: 1 – the initial state of the RFE with a size of \( d_1 \), 2 – after loading in the austenitic state, 3 – the sample after the deformation of the plasticity of the transformation with the dimension \( d(t) \).

Figure 6. The effect of cooling rate on oval shaping: 1 – cooling with a thermostat; isothermal cooling: 2 – at 300 K, 3 – at 280 K, 4 – at 270 K.
To analyze the causes of the results obtained, a numerical experiment was performed. A calculation is made of the evolution of the temperature field in a cylinder when its surface is cooled from 400 K to \( M_f = 313 \text{ K} \) (the temperature of the end of the direct martensitic phase transition) and to a temperature 40 K below \( M_f \). The calculations were performed using the heat equation [4] in cylindrical coordinates (1):

\[
\rho \cdot c(U) \cdot \frac{\partial U}{\partial t} = k \cdot \left( \frac{\partial^2 U}{\partial r^2} + \frac{1}{r} \cdot \frac{\partial U}{\partial r} \right)
\]  

where \( \rho \) is the density of the material, \( k \) is the coefficient of thermal conductivity, \( U \) is the temperature, \( r \) is the radial coordinate, \( t \) is the time. The heat capacity \( c(U) \) outside the transformation temperature range is a constant \( c_0 \), and in the temperature range the lattice rearrangement is approximated by a quadratic function (2):

\[
(U) = c_1 \cdot \frac{(U-M_s)(M_f-U)}{(M_f-M_s)^2} + c_0
\]

where \( M_s \) is the onset temperature of the direct transformation (in the numerical experiment 323 K). The value of the constant \( c_1 \) is found from equation (3):

\[
Q_{tr} = \int_{M_s}^{M_f} c_1 \cdot \frac{(U-M_s)(M_f-U)}{(M_f-M_s)^2} dU
\]

where \( Q_{tr} \) is the latent heat of transformation.

**Figure 7.** The evolution of the temperature field with a direct martensitic transformation in a cylinder \( r = 1 \text{ mm} \) with a sharp change in surface temperature from 400 K to \( M_f \) (1) to \( M_f - 40 \text{ K} \) (2).

In figure 7, it can be seen that the supercooling of the cylinder causes the heterophase zone to move from the sample surface to the center by a narrow band. At the same time, at the \( M_f \) temperature on the cylinder surface, the heterophase state \( V_{het} \) covers almost the entire volume of cylinder \( V \). At the same time, the lifetime of this state is much longer (figure 8). Similar results were obtained for heated cylinders.
Figure 8. Evolution of the direct martensitic transformation zone $V_{\text{get}} / V$ in a cylinder $r = 1$ mm over time with a sharp change in surface temperature from 400 K to $M_f$ (1) to $M_f - 40$ K (2).

3. Conclusion

Thus, an extensive heterophase state and its duration provide an improvement in the deformability of the force element during the cooling process. When heated, this is done only partially. The phenomena of countercurrent compete with the change in shape due to the effect of shape memory. The advantage in the development of deformation processes is on the side of the SME.

When creating structures made of titanium nickelide, it is necessary to take into account the technological conditions of their operation, due to the temperature conditions of equipment operation.

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