The effect of generating reactive stresses in the spring elements of titanium nickelide

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Abstract. The article is devoted to the study of the effect of generation of reactive stresses in tension springs. The studies of the kinetics of generation and relaxation of these stresses in the TiNi alloy are presented. Regularities of the change in reactive stresses during long-term thermal cycling in the range of complete and incomplete MPs are considered. It was established that the level of reactive stresses depends on several factors, such as the degree of pre-deformation, the type of stress state, the stiffness of the opposing system, the strength properties of the alloy.

1. Introduction
The effect of generation of reactive stresses in materials with shape memory is becoming more widely used in various fields of technology and even medicine [1, 2]. Helical springs [3] are used as executive elements in many mechanisms, which allow creating large axial displacements and regulating the developed reactive forces by changing the spring's geometrical parameters. However, despite such wide possibilities of alloys with SME, their use is limited by the instability of the thermomechanical behavior under various heat shift conditions. Therefore, the study of the laws governing the change in reactive stresses during long-term thermal cycling in the range of complete and incomplete MP spring elements is relevant.

2. Objectives and research methods
In this work, we studied the effect of generation of reactive stresses in tension springs (figure 1) from titanium nickelide of equiatomic composition.

![Figure 1. Extension spring: a) – initial condition; b) –deformed state.](image-url)
Springs were coiled from nickel-titanium wire of equiatomic composition with various geometrical parameters $d$, $D_0$, $n$ on special mandrels. The specified form was obtained by annealing in a pinched state at a temperature of 500 °C for one hour.

For the calculation of stresses and relative deformation, we used the formulas of the resistance of materials taking into account the elastoplastic behavior of EPP alloys. Reactive stresses were calculated by the formula (1)

$$\tau = \frac{6PD_0}{\pi d^3}$$

where: $P$ – is the axial force, H; $D_0$ – is the average diameter of the spring, mm; $d$ – is the diameter of the wire, mm;

Relative deformation was calculated by the formula (2)

$$\gamma = \frac{\Delta l d}{\pi D_0^2 n}$$

where: $\Delta l$ – is the axial deformation of the spring, mm; $n$ – the number of turns of the spring;

Similar formulas for calculations were used by the authors in studies of the thermomechanical behavior of springs [4, 5]. The magnitudes of reactive stresses and relative deformations determined on springs of different geometric shapes with the same loading conditions were the same, which indicates the validity of using these formulas.

The study was conducted on the installation, the scheme of which is shown in figure 2.

![Figure 2. Installation diagram: 1– tensile machine; 2– control panel; 3 –computer; 4 – tube furnace; 5 – thermocouple; 6 – LATR; 7 – transformer; 8 – lower traverse; 9 – upper traverse.](image)

When the spring was gradually heated by a laboratory transformer (6), reactive forces were generated in the material through an interval of martensitic transformations, which were recorded by the control panel of the bursting machine (2). The heating temperature was controlled by a thermocouple installed in the furnace and connected to the input of the computer. The signal from the control panel is also connected to the computer input and a hysteresis loop generating reactive forces during heating and their relaxation during cooling was recorded on the screen.
The kinetics of generation and relaxation of these stresses in the TiNi alloy is shown in figure 3. The sample was pre-stretched in the martensitic state at 270 K to a residual elongation of 2.7% and fixed in supports, the rigidity of which was infinite relative to the rigidity of the sample. Thermal cycling was carried out both through the entire interval of phase transformations and the incomplete interval $\Delta T^H$.

![Figure 3. The effect of generation and relaxation of reactive stresses.](image)

3. Results and discussion

The magnitude of the generated stresses closely correlates with the amount of the high-temperature phase that appeared during the warm-up process, and the temperatures $A_b^\sigma$ and $A_e^\sigma$ correspond to the beginning and end of the reverse martensitic reaction of the stressed metal. During cooling, relaxation of stresses is observed in accordance with the kinetics of the development of plasticity of direct transformation. The fall in stresses begins with a temperature $M_b^\sigma$ and ends at a temperature lying in the interval $M_b^\sigma - M_e^\sigma$. The temperature $M_b^\sigma$, as well as the temperature $A_e^\sigma$, strongly depends on the magnitude of the generated stresses. For titanium nickelide, the elevation of these temperatures over $M_b$ and $A_e$ reaches one hundred and more degrees [6].

The generation of reactive stresses is observed after preliminary deformation. The maximum level of reactive stresses $\sigma_r^{\text{max}}$ increases with increasing degree of pre-deformation ($\varepsilon_{pr}$) and stiffness of the reaction system ($K_{pr}$). Under conditions of torsion and bending, an increase in $\varepsilon_{pr}$ or $\gamma_{pr}$ is accompanied by a smooth increase in $\sigma_r^{\text{max}}$ and $\tau_r^{\text{max}}$ (curves 1, 2 in figure 4a). Under the conditions of stretching, the $\sigma_r^{\text{max}} - \varepsilon_{pr}$ dependence (curve 3, figure 4b) has a sharp bend, due to the fact that the maximum stress level is determined by the yield strength of austenite $\sigma$. When reactive stresses reach $\sigma$, their further increase is limited by the plastic flow stress of austenite. At $K_{pr} = 0$, the molding restoration in a state free from stresses leads to the complete or partial return of a given deformation. With an absolutely rigid clamping of the $K_{pr} \to \infty$, the restoration of the form is prohibited, and the material generates efforts, the magnitude of which is determined by the degree of preliminary deformation and the mechanical properties of the material.
Figure 4. The effect of pre-strain on the level of reactive stresses in TiNi alloy.

With the final stiffness of the pinching, both the generation of stresses and the return of deformations occur simultaneously. The magnitude of the generated stresses increases with increasing stiffness of the reaction.

The level of maximum reactive stresses $\sigma_{r\text{max}}$ can be estimated from the loading curve of a material with an SME in the austenitic state (figure 5).

Figure 5. Dependence of reactive stresses $\sigma_r$ on the value of preliminary deformations $\varepsilon_{pr}$ (curve 1) and the tension diagram at a temperature of 150 °C (curve 2) for TiNi alloy.

From figure 5 it can be seen that reactive stresses differ little from tensile stresses of austenite. This result is of practical importance, since it is easy to calculate the magnitude of reactive stresses for arbitrary sizes of curves of rods with the required values of force using the well-known austenite stretching diagram.

A characteristic feature of the kinetics of reactive stresses is the ability to reproduce a virtually unlimited number of times the stress-temperature hysteresis during repeated heating and cooling [7]. If the material that has experienced complete or partial stress relaxation is reheated in a clamped state to the temperature $\Delta T$, then the stresses will arise according to the original scheme. Repetitive heat shifts either slightly reduce the level of reactive stresses, or slightly increase it depending on the chemical composition of the alloy, its structural state, but after a certain number of thermal cycles, the hysteresis loop stabilizes.

A cyclical study of TiNi alloys in the form of springs, in the first cycles, a sufficiently effective drop in the level of reactive stresses is observed, and then after 10–20 cycles the process stabilizes, that is,
the further nature of \( \sigma_r \) change for titanium nickelide is determined by a linear law. It was noted that after 1600 heat cycles even a certain increase in reactive stresses is observed, in accordance with figure 6, curve 1, due to phase hardening and an increase in the dislocation yield strength. In the range of 2000–4500 cycles, the PH practically does not change.

The character of the curve \( \sigma_r = \sigma_r(N) \) in the case of a soft pinching (a spring with a SME – counter spring) is somewhat different. First, there is no marked anomaly in the thermocyclic behavior of titanium nickelide in the case of finite stiffness, in accordance with figure 6, curve 2, and, second, the full stabilization of the process of thermomechanical deformation occurs only after 6500 cycles.

The authors of [8] suggested that the nature of the thermal cyclic behavior of TiNi alloys is significantly affected by the pinching stiffness, the degree of preliminary deformation, the cycling interval, the composition of the alloy, etc.

![Figure 6](image)

Figure 6. The change in reactive stresses during thermocycling of titanium nickelide:
1 – the case of severe pinching, \( \gamma_{pr} = 3.5\% \); 2 – mild opposition \( \gamma_{pr} = 3.0\% \).

In the mechanisms of two-sided action, the working spring – counter-spring material with SME works under conditions of finite stiffness of the reaction, generating reactive stresses \( \tau_n \). When heated to a predetermined temperature of the \( A_n^u \). During subsequent heat changes in a given temperature range \( \Delta T^n = A_n^u - M_n^u = T_{\text{max}} - T_{\text{min}} \), cooling takes place during cooling, and during heating, the generation of stresses, the change of which is characterized by a voltage swing \( \Delta \tau \). Consequently, the thermocyclic operability of interconnected elements under conditions of incomplete MPs will be determined by the stability of the reactive stresses generated by the alloy \( \tau_n \) and the magnitude of the stresses \( \Delta \tau \).

Thermocyclic performance studies were carried out on spring samples made of an alloy of Ti = 50.2% Ni with given geometrical sizes. The thermocycling interval \( \Delta T^n = A_n^u - M_n^u \) was chosen in such a way as to ensure the condition of incomplete phase transformation. The change in reactive stresses during heat changes was studied with two values of the stiffness of the counteraction of the \( K_{pr} \), determined by the stiffness of the counter spring. The value of the preliminary deformation was taken equal to \( \gamma_{pr} = 3\% \).

The effect of preliminary thermal testing on the cyclic performance of the material was also investigated. To do this, before testing, the samples were cycled (20 and 40 cycles) through the full MP interval under a constantly applied stress \( \tau = 50 \text{ MPa} \). The dependence of reactive stresses and stress range on the number of thermal cycles is presented in figure 7:

1, 6 – \( K_{pr} = 41 \text{ GPa} \); 2, 7 – \( K_{pr} = 15.2 \text{ GPa} \) – without thermal testing;
3, 8 – $K_{pr}=41 \text{ GPa}$; 4, 9 – $K_{pr}=15.2 \text{ GPa}$ – thermal testing 20 cycles;
5, 10 – $K_{pr}=15.2 \text{ GPa}$ – thermal testing 40 cycles.

Studies show that the nature of changes in reactive stresses is almost the same for different values of the stiffness of pinching and varies greatly depending on the preliminary thermocyclic treatment.

Thermal testing leads to stabilization of the stresses $\tau_{n}$ and $\Delta \tau$, which remain unchanged from the first thermal cycles. Only at the initial stage there is a slight decrease in $\tau_{n}$.

An increase in the duration of thermal testing from 20 to 40 cycles has practically no effect on the functional and mechanical properties, which indicates that twenty preliminary thermal cycles are sufficient to stabilize the reactive stresses during thermal cycles in a narrow temperature range.

In untrained samples with thermal changes, an insignificant increase in $\tau_{n}$ is first observed. This is associated with a decrease in the characteristic temperatures of martensitic transformations in the process of cycling, which, at a fixed $A_n$ temperature, leads to an increase in the degree of reverse phase transition and, accordingly, to an increase in $\tau_{n}$.

The subsequent decrease in stresses is determined by the processes of thermocyclic creep, which are most pronounced in samples that have not been subjected to thermal cycling.

![Figure 7](image_url)

*Figure 7.* The change in the level of reactive stresses (a) and the range of stresses (b) in the Ti alloy is 50.2% at % Ni during thermal cycling in the interval of incomplete MP. $\Delta T^{II} = 15K$ in conditions of the finite stiffness of counteraction of the $K_{pr}$ ($\gamma_{pr}=3.0\%$).
4. Conclusion
The conducted studies show that the preliminary thermal training is necessary for the stabilization of the thermomechanical properties under conditions of incomplete MPs, which remain unchanged for a long term thermal cycling. Thus, we can conclude that the level of reactive stresses depends on several factors, such as the degree of pre-deformation, the type of stress state, the stiffness of the opposing system, and the strength properties of the alloy. The magnitude of the reactive forces during heating is proportional to the amount of austenite formed, and the nature of the relaxation of forces is determined by the growth of crystals of the new phase (martensitic) in the field of external stresses with decreasing temperature.

References
[1] Jiang P, Zheng Y, Tong Y, Chen B, Tian, L Li, Gunderov D and Valiev R 2014 Transformation hysteresis and shape memory effect of an ultrafine-grained TiNiNb shape memory alloy Intermetallics 54 133–135
[2] Gusev D, Kollerov M and Sharonov A 2015 A study of reactive stresses generated by implants from titanium nickelide-based alloys Titanium 1 42–49
[3] Khusainov M, Larionov A, Malukhina O and Tambulatov B 2001 Thermal Valve RF patent for invention No. 2171937 from 01/27/2001 Publ. 08/10/01 Bul 22
[4] Andronov I, Demina M, Kormshchikova Z and Matveeva O 2017 The influence of incomplete thermal cycles on the performance of a helical coil spring made of titanium nickelide Deformation and fracture of materials 8 51–58
[5] Abdrakhmanov S, Dotalieva Zh and Abdyzhapar A 2017 Analytical study of the deformation-force behavior of conical springs with shape memory effect Deformation and fracture of materials 9 32–46
[6] Mashikhin A, Kazarina S and Movchan A 2016 Generation of reactive stresses in the investigation of oriented transformation of a shape memory alloy in a bent state Bulletin of Tambov University 3 1152–55
[7] Tong Y, Chen F, Guo B, Tian B, Li L, Zheng Y, Gunderov D and Valiev R 2013 Superplasticity and its stability of an ultrafine-grained Ti49.2Ni50.8 shape memory alloy processed by equal channel angular pressing Materials Science and Engineering: A Vol 587 61–64
[8] Belyaev S, Volkov A and Evard M 2017 Modeling irreversible deformation and destruction of titanium nickelide during thermal cycling Deformation and fracture of materials 4 65–73