Distribution of thermophysical and mechanical properties of titanium nickelide in the welding zone

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Abstract. The paper analyzes the behavior of the deformation characteristics of welded joints made of TiNi alloy with a shape memory effect. Comparison of the level of tensile strength of welded samples made by the TIG method in an Ar and He atmosphere was carried out using an Instron 5985 universal machine. The study of the material structure in the weld zone and the heat-affected zone was carried out on longitudinal sections using a JSM-6490LV electron microscope. To estimate the mechanical parameters PMT-3 microhardness tester was used. The calorimetric parameters of the welded samples were obtained using a differential scanning calorimeters METTLER TOLEDO 822e and TA Instruments Q20. To analyze the gradient properties at the weld zone and the heat-affected zone, the temperature fields were calculated using the thermal conductivity equation included in the model of the residual stress mechanism.

1. Introduction
The development of mechanical engineering, using materials with shape memory effect, requires the development of new technological methods necessary for the creation of original mechanisms. Welding provides great opportunities for solving technical problems. This is not a new technology, but it is rarely used in the manufacture of mechanisms from TiNi alloy and other materials with shape memory effect. The cause of this is a significant loss of strength properties of the material in the welded joint zone. Therefore, the identification of factors that fracture the structures and the search for methods for their neutralization is an urgent task.

2. Research results
Samples for studying the strength properties of welded joints were made from 2 mm wire of TiNi 55.42 wt. % alloy. Welding was carried out in two modes. In an argon atmosphere the
technological operation lasted ~ 3 s, with a constant electric current $I = 10$ A. In a helium atmosphere the technological operation lasted ~ 1.5 s with an electric current $I = 45$ A. The deformation and strength properties of welded samples under tension were studied on an Instron 5985 testing machine. Before strength testing, some of the samples were annealed at 500 °C for 30 min followed by cooling in the furnace. Some of them were subjected to thirtyfold thermal cycling by the transition of the alloy from the martensitic state to the austenitic one and vice versa.

The dependency between deformation and stress under tension is shown in Figure 1. A sample from a single piece of the original wire (curve 1, Figure 1) was elastically deformed to $\varepsilon = 0.005$ and stresses ~120 MPa. With load increasing for stress $\sigma$ about 160 MPa and deformation $\varepsilon$ of 0.055 at the stage of hardening begins. When $\sigma \sim 1050$ MPa is reached, the second yield line begins. With an increase in $\varepsilon$ from 0.11 to 0.20, the stress does not change its value. In almost all other samples, the initial stage of deformation is similar to the original samples. Only welding in a helium atmosphere without additional heat treatment showed the deformation of the first yield line begins under a stress of ~210 MPa. A sample prepared in an Ar atmosphere with subsequent annealing (curve 2, Figure 1) changed during loading similar to the behavior of the initial state of the wire. For three other variants, hardening begins at $\varepsilon \sim 0.045$. Fracture of four welded samples occurred at $\sigma$ from 450 MPa to 580 MPa. Similar results were obtained in the study of joints by electric welding. [1-3].

![Figure 1](image1.png)

**Figure 1.** Strength properties of wire samples of TiNi 55.42 wt. %: 1 – initial, 2–5 – samples welded in Ar, $I = 10$ A (2), He, $I = 45$ A (3,5), He + 30 thermocycles, $I = 45$ A (4); 1–4 – with anneal ($T = 500$ °C), 5 – without anneal. The motion speed of the movable holder is 4 mm/min for curves 1, 2, and the speed is 1 mm/min in the rest of cases.

A JSM-6490LV microscope was used to study the structure of the welded joint zones. Figure 2a shows a longitudinal section of the welded sample that has not been tested for strength. Figure 2b shows the weld zone and heat-affected zone of a fractured sample.

Analysis of photographs of the welded joint sections showed that in the boundary of the weld zone and the heat-affected zone on the surface, there are cracks with a depth up to 20 μm (Figure 3a). During the deformation of the sample, these cracks seem to develop. Figure 3b shows cracks at the boundary of the weld zone and the heat-affected zone on the opposite side of the fracture zone.
Measurements have shown that the size of these defects reaches 200 μm in depth. Thus, the depth of the surface crack has increased by an order of magnitude.

![Figure 2](image1.png)  ![Figure 2](image2.png)

**Figure 2.** Longitudinal thin sections of a welded joint obtained in an He atmosphere, \( I = 45 \text{ A} \) (c), the fracture zone of a sample welded in an Ar atmosphere, \( I = 10 \text{ A} \) (b).

![Figure 3](image3.png)  ![Figure 3](image4.png)

**Figure 3.** Crack at the boundary of the weld zone and heat-affected zone: a – before loading, point C (atmosphere – He, \( I = 45 \text{ A} \)), b – after destruction, point G (atmosphere – Ar, \( I = 10 \text{ A} \)).

Features at the boundary of the weld zone and the heat-affected zone were also noted when measured the microhardness. For this purpose PMT-3 microhardness tester was used. Measurements of microhardness changes were carried out along the longitudinal section of the welded sample obtained in He atmosphere. Figure 4a shows that the microhardness of weld zone significantly exceeds the values of the mechanical characteristics in the heat-affected zone. Annealing of the sample (500 °C for 30 min) slightly reduces the average value of the microhardness of the weld zone (Figure 4b). Noteworthy is the non-monotonicity of the change in the mechanical characteristics in the heat-affected zone when moving away from the weld zone boundary. The maximum value of microhardness is noted both in the initial sample and in the annealed sample at a distance of 3-4 mm from the weld zone boundary.
Figure 4. Microhardness of the welded joint of the sample welded in a He atmosphere ($I = 45$ A): a – without heat treatment, b – with annealing ($500$ °C, 30 min).

Besides microhardness characteristics in this area change substantially and calorimetric parameters of martensitic transformation in the material. Figure 5a shows curves, obtained on a differential scanning calorimeter (DSC) METTLER TOLEDO 822e at the boundary of the weld zone and the heat-affected zone. Comparing this information with the data on the adjacent section of the sample from the heat-affected zone, obtained with the DSC TA Instruments Q20, it should be noted that during heating, the peak of the endothermic reaction was recorded in the first case at 46.14 °C, and in the second – at 38.0 °C (Fig. 5b). Significantly different values of $Q_r$, conversion specific heat. In the weld zone, a value of 23.4 J/g was obtained. In the heat-affected zone, $Q_r$ is 20.43 J/g. Welding in an argon atmosphere is characterized by close values of the position of the maxima of the endothermic reaction on the temperature scale. In the weld zone, it is 45.0 °C, and in the heat-affected zone, 37.8 °C (Figure 6). For the specific latent heat of transformation, the value in the weld zone was obtained close to the corresponding value of the sample prepared in a helium atmosphere, 23.33 J/g. For the adjacent section in the heat-affected zone, this characteristic is 10 % less – 18.22 J/g.

To assess the causes for this difference in the parameters of the material in the weld zone boundary, a numerical experiment was carried out. The calculation of the time dependence of the temperature in the weld zone and in the adjacent section of the heat-affected zone at a distance of 1 mm from the boundary has been carried out.
A one-dimensional heat conduction equation was used taking into account convective heat exchange with the environment:

\[
\rho \cdot c(U) \cdot \frac{\partial U}{\partial t} = k \cdot \frac{\partial^2 U}{\partial x^2} - \frac{2\alpha}{r} (U - U_{\text{env}}),
\]

(1)

where \( \rho \) – the material density, \( c(U) \) – the heat capacity, \( U \) – the temperature, \( t \) – the time, \( k \) – the thermal conductivity coefficient, \( x \) – the spatial coordinate, \( \alpha \) – the heat transfer coefficient, \( r \) – the radius of the wire, \( U_{\text{env}} \) – the ambient temperature. In the single-phase state \( c(U) = c_0 \) – is a constant. In the range of direct martensitic transformation, the heat capacity is approximated by a quadratic function:

\[
c(U) = c_1 \cdot f(U) + c_0,
\]

(2)

where \( f(U) \) – distribution of the latent heat of the phase transition over the transformation temperature range. The coefficient \( c_1 \) is determined from the equation:

\[
Q_{tr} = \int_{M_L}^{M_T} c_1 \cdot f(U) dU,
\]

(3)

where \( Q_{tr} \) – is the specific value of the transformation latent heat. The constants for the material in the mathematical model were chosen to be close to the characteristics of titanium nickelide. It was
assumed that in the weld zone the temperature changes abruptly, reaching levels at which titanium nickelide is in a liquid state. At the same time, taking into account different values of the current force during welding in an atmosphere of argon and helium, calculations were carried out with different initial temperatures of the weld zone. Figure 7a shows the evolution of temperature in a «cold» welding. «Hot» welding corresponds to the time dependence of temperature in Figure 7b. From a comparison of the curves in these figures, it follows that the temperature drop at the crystallization onset time is almost 2 times higher than in the case of «hot» welding. During the subsequent cooling it apparently leads to the formation of internal stress field, the presence of which significantly change calorimetric characteristics of martensitic transformation in the material.

![Figure 7](image)

**Figure 7.** Qualitative assessment of temperature at control points: 1 – central part of the welded joint, 2 – 1 mm from weld zone; welding temperature: a – 1700 °C, b – 2500 °C.

3. Conclusion
The results show that TiNi alloy is in a gradient state at the boundary of the weld zone and the heat-affected zone. This is evidenced by the data from studies of microhardness and a comparison of the calorimetric characteristics of martensitic transformations in titanium nickelide at the boundary of the weld zone and the heat-affected zone. The consequence of this is the defects observed in this area in photographs obtained using an electron microscope. Apparently, this is the cause of the fracture of the welded samples. It can be assumed that an increasing of the temperature of the welded metal and the selection of the parameters of the electric current will improve the characteristics of the welded joint for materials of this class.

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