Mechanical properties of weld joints of TiNi alloy wire used in force elements

E A Khlopkov1,2,5, D V Kurushkin1, E S Ostropiko2,3, V M Khanaev4, S B Sapozhkov2 и Yu N Vyuenko4

1 Peter the Great Saint Petersburg Polytechnical University, Saint Petersburg, 195251, Russia
2 Yaroslav-the-Wise Novgorod State University, ul. B. St. Petersburgskaya, 41 173003 Veliky Novgorod, Russia
3 Saint Petersburg State University, Saint Petersburg, 198504, Russia
4 OOO «OPTIMIKST LTD», Saint Petersburg-Novosibirsk, 195426, Russia

5E-mail: hlopkovelisey@mail.ru

Abstract. The paper presents data on the mechanical testing of argon-arc weld joints of the TiNi 55.42 % wt. wires diameter of 2 mm. The mathematical modeling results of the temperature fields evolution of the weld zone during cooling are given.

1. Introduction
Currently, such functional materials as alloys with shape memory effect (SME) are widely known [1]. These metals begin to find their application in the space industry and medicine [2–4]. However, in modern engineering technology [5–10] there are practically no technical solutions implemented with the help of unique properties of materials with SME. The exception is ring force beam elements (RFBE, "metal muscles") of nickelide titanium [11]. These compact drives are actuators of the press used in the manufacture of anti-vibration layered compositions. For ten years, "metal muscles" demonstrate trouble-free operation in the process. In this case, their mechanical properties were investigated depending on various technological conditions [12–15]. However, the use of RFBE in work in the reversible shape memory (RSM) mode was undertaken only with the advent of hard TiNi wire joints [16]. The authors [16] managed to obtain the strength of the weld of a wire with a diameter \( d = 2 \) mm equal to 66% of the starting material. In the works [17], the authors were able to make welded joints capable of withstanding a force of up to 80% of the applied to the starting material before breaking. However, this level of strength was obtained when welding wire was with \( d \) less than 1 mm.

The aim of this work was to search for ways to improve the quality of welded joints of wire from TiNi alloy to create RFBE, capable of operating in the RSM mode. For experimental research, a wire of \( d = 2 \) mm from TiNi55, 42 wt. percentage. Welding was carried out in two modes by argon-arc welding.

2. Results and discussion
In the first case, a welded joint was obtained using the Svarog TIG P AC / DC source in an \( Ar \) atmosphere. A voltage of 12 V and a current of 10 A were set at the source. Figures 1 and 2 show the plots of the interdependence of deformations and applied stresses, which make it possible to estimate the strength characteristics of a wire sample from the source material and welded samples. Mechanical
tests were performed on an Instron universal machine, under conditions when the material was in the martensitic state. The traverse speed was 1 mm / min.

Figure 1. Strength properties of the original TiNi sample.

Figure 2. Strength properties of welded TiNi samples: 1 – mode 1 with heat treatment, 2 – mode 2 with heat treatment, 3 – mode 2 without heat treatment, 4 – mode 2 with heat treatment and thermal cycling.

Up to a stress of 120 MPa, the deformation $\varepsilon = \Delta l/l_0$ accumulated according to Hooke's law up to 0.4% (figure 1). A further increase in stresses up to 160 MPa translates the process of deformation into the plastic flow regime. This process is maintained up to $\varepsilon = 6\%$. Further, the magnitude of the deformation increases with $\sigma$ according to a law close to linear. Exceeding the level of 900 MPa transfers the deformation process into submission to the law of plastic flow. Achieving a voltage level of 1060 MPa and exceeding $\varepsilon$ of 20% leads to the destruction of the sample.

Curve 1 in figure 2 shows that in the first technological mode, it was possible to obtain a welded specimen with a breaking load of 40% of the corresponding value of the source material (figure 1).
Before mechanical testing, annealing was performed at \( T = 773 \text{ K} \) for 30 min, then cooled with a furnace. This heat treatment (HT) was performed to eliminate residual stresses in the material of the weld zone.

The second welding mode was performed on the EWM Force TIG 552 apparatus. The voltage was set at 18.5 V, the current strength being 45 A. Ne was used as a protective atmosphere in the technological operation. Curve 2 in figure 2 shows that in this mode it was possible to make a welded joint with a strength of up to 55% of the original sample. Before the breaking tests, the welded core was heat-treated the same as the starting material. Without annealing, the welded specimen collapsed at a load two times smaller than the limiting force effect on the solid piece of wire (curve 3, figure 2).

The fourth sample, the compound of which was made in the second mode, besides annealing, was subjected to thermal cycling through the interval of direct and reverse transformation. For this, the sample was alternately placed in a thermostat chamber with a temperature of 100 °C and a refrigeration chamber with a temperature of \((-2) \text{ °C}\). The exposure time in isothermal conditions was equal to 15 minutes. This made it possible to transfer the material completely from the austenitic state to the martensitic state and back. The performed procedure did not increase the strength of the sample (curve 4, figure 2). The destruction took place practically under the same load as the third one. However, the deformability was higher. At lower stresses, the sample showed a greater elongation than a similar one without heat treatment (curve 3, figure 2).

To analyze the characteristics of the state of the wire material in the welding zone, a numerical experiment was performed in which the evolution of the temperature field was studied. It was assumed to simplify the calculations that heat exchange with the environment does not occur. As a result of the immediate impact of electric current, the material in the welding zone is heated to 1000 °C. The temperature distribution along the wire corresponds to curve 1 in figure 3. On a wire segment from 0 to 0.5 mm, the temperature is 1000 °C, the rest of the wire material is at room temperature 25 °C. Further, the evolution of the temperature field was calculated using the one-dimensional heat conduction equation (1):

\[
\rho \cdot c(U) \cdot \frac{\partial U}{\partial t} = k \cdot \frac{\partial^2 U}{\partial x^2} \tag{1}
\]

where \( k \) is the coefficient of thermal conductivity, \( U \) is the temperature, \( t \) is the time, \( x \) is the linear coordinate, \( \rho \) is the density of the material. The heat capacity of the material \( c(U) \) depended on temperature. This made it possible to take into account the latent heat of martensitic transformation. Distribution of the latent heat of the phase rearrangement of the crystal lattice quadratic function was approximated (2):

\[
c(U) = c_0 + c_1 \cdot \frac{(U-A_s)(A_f-U)}{(A_f-A_s)^2} \tag{2}
\]

where \( c_0 \) is the heat capacity of the single-phase state. This value was considered constant and the same for low-temperature and high-temperature states. Respectively, \( A_s \) and \( A_f \) are the temperature of the beginning and end of the reverse transformation. For the model experiment, these values were assumed to be 60 °C and 70 °C. The second constant \( c_1 \) was determined from the relation (3):

\[
\int_{A_s}^{A_f} c_1 \cdot \frac{(U-A_s)(A_f-U)}{(A_f-A_s)^2} dU = Q_{tr} \tag{3}
\]

where \( Q_{tr} \) is the latent heat of the martensitic transformation.
Figure 3. The evolution of the temperature field in the welding zone in the absence of phase transformation under cooling conditions at the moment of time: 1 – 0 s, 2 – 5 s, 3 – 10 s, 4 – 20 s.

Figure 4. The evolution of the temperature field in the welding zone with the presence of phase transformation during cooling at the time point: 1 – 0 s, 2 – 5 s, 3 – 10 s, 4 – 20 s.

To simplify the problem, we assume that the direct transformation proceeds in the material below room temperature. For comparison with materials that do not undergo transformations, the problem of the evolution of the temperature field was solved when, in equation (1), $c(U) = c_0$ over the entire temperature range from 25 °C to 1000 °C. Figure 3 shows the distribution of heat at different times in the absence of phase transformations. Comparing with the curves similar in time in figure 4, we see that the phase transition with the latent heat of transformation significantly speeds up the process of cooling.
the welding zone. Figure 5 shows that with increasing $Q_{tr}$, the rate of temperature decrease in the interval from 0 to 0.5 mm increases.

![Temperature field distribution in the welding zone at the moment of time 20 s with the latent heat of transformation $Q_{tr}$: 1 – 0 kJ / kg, 2 – 20 kJ / kg, 3 – 40 kJ / kg, 4 – 200 kJ / kg.](image)

**Figure 5.** Temperature field distribution in the welding zone at the moment of time 20 s with the latent heat of transformation $Q_{tr}$: 1 – 0 kJ / kg, 2 – 20 kJ / kg, 3 – 40 kJ / kg, 4 – 200 kJ / kg.

The analysis of the obtained curves shows that in the wire segment, in the final analysis, there are three sections with a different structure (figure 6). The austenitic state of the material is formed in the adjacent welding zone. With sufficient length, the austenitic state will be followed with a heterophase zone, in which the ratio of austenite and martensite will change as the distance from the zero point changes. Further, the alloy will remain in the original martensitic state. In this way, a clearly heterogeneous material of the simplest welded structure was obtained. It can be assumed that the rate of cooling of the weld zone may introduce additional features in the structure of the material of the construction. Such a gradient system will require not only additional heat treatment in the form of annealing, but also for structures of multiple action, as M.A. Khusainov repeatedly noted [18]. It will be necessary at least fifteen times thermocycling of the annealed part with the transfer of material from martensite to austenite and back to stabilize the temperature ranges of phase transitions.

![Welded joint areas in the TiNi alloy: WZ – joint area, A – austenitic section, HZ – heterophase state of the material, M – martensitic region.](image)

**Figure 6.** Welded joint areas in the TiNi alloy: WZ – joint area, A – austenitic section, HZ – heterophase state of the material, M – martensitic region.
3. Conclusion
Thus, the welding technology will require the development of special heat treatment regimes, focused on the upcoming technological conditions of operation of the fabricated structure.

Acknowledgments
The reported study was funded by RFBR, project number 19-38-90285.

References
[1] Likhachev V A, Kuzmin S L and Kamentseva Z P 1987 The shape memory effect (Leningrad: Leningrad State University) p 216
[2] Belyaev S P, Volkov A E, Ermolaev V A at al 1998 Shape Memory Materials: Reference Book (St. Petersburg: NIIKh SPbGU)
[3] Kravchenko Y D, Likhachev V A, Razov A I, Trusov S N and Cherniavsky A G 1966 Testing of shape memory alloys in the erection of large-scale structures in open space Technical Physics 41 1167–1171
[4] Gyunter V E, Kotenko V V, Polenichkin V K and Itin V I 1985 Use of alloys with shape memory in medicine Soviet Physics Journal 28 433–437
[5] Anukhin I V, Anukhin V I, Lyubomudrov S A and Murashkin S L 2015 Thermal imaging in selecting the cutting conditions for high-temperature intermetallic alloys Russian Engineering Research 35 544–548
[6] Kolodyazhniy Y Y, Lyubomudrov S A and Makarova T A 2016 Quality assurance issues of hard-processing aluminum alloy parts fabrication for aircraft construction and engine-building Journal of Engineering and Applied Sciences 11 3019–3023
[7] Kozar I I, Kolodyazhniy D Yu, Radkevich M M Tsimko TA 2014 A mathematical model of error for intractable alloy turning Nauchno-tekhnicheskie vedomosti SPbGPU 2 194–201
[8] Tarasov S B, Stepanov SN 2007 Development of the reference and high precision instruments and devices for replacing foreign-made equipment Nauchno-tekhnicheskie vedomosti SPbGPU 4 29–33
[9] Nikitkov N V, Kovelenov N Y and Shabalin D N 2012 Calculation mode cuttings under diamond cutting stocking up from hard frail material Nauchno-tekhnicheskie vedomosti SPbGPU 3 155–159
[10] Zhukov E L, Kozar I I and Olodyazhniy D Y 2016 Problems of ensuring quality of a surface layer when producing components from hard-to-process heat resistant alloys Acta Metallurgica Slovaca 22 128–132
[11] V’yunenko Yu N, Volkov G A and Khlopkov E A 2018 Temperature factor to control deformation–power behavior of ring-shaped bundle force TiNi elements Technical Physics 63 1167–1170
[12] Khlopkov E, Volkov G and V’yunenko Yu N 2017 Specific features of the behavior of TiNi force elements in thermocycling Materials Today: Proceedings 4 4879–4883
[13] Kiselev A Yu, Belousov N N, Khlopkov E A and V’yunenko Yu N 2018 The effect of the size factor on the functional properties of shape memory alloy ring-shaped force elements Materials Research Proceedings 9 24–27
[14] V’yunenko Yu N 2013 Mechanical characteristics of the power element of materials with SME Tambov University Reports. Series: Natural and Technical Sciences 18 2023–2024
[15] Khlopkov E A and Vyunenko Yu N 2018 Influence of cooling rate on the deformation processes associated with direct martensitic transformation in TiNi alloy Materials Research Proceedings 9 28–31
[16] Vyunenko Yu N and Belousov N N 2018 Two-way shape memory effect in ring-shaped designs Actual Problems of Strength 482–484
[17] Nishikawa M, Tanaka H, Kohda M, Nagaura T and Watanabe K 1982 Behaviour of welded part of Ti-Ni shape memory alloy Journal de Physique Colloques 43 839–844
[18] Khusainov M and Volnyanskaya O Y 2001 Influence of the preliminary thermocycling mode on the deformation-force parameters of the shape memory alloy *Modern Problems of Strength* **P** 2 123–127