ISSN 1063-7834, Physics of the Solid State, 2018, Vol. 60, No. 6, pp. 1190–1194.

Delay Effect for Pulsed Excitation of Actuator Based on Rapidly Quenched Ti_2NiCu Alloy with Thermoelastic Martensitic Transformation

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Received December 25, 2017

Abstract—The pulse response of the actuator based on rapidly quenched Ti_2NiCu alloy with a thermoelastic martensitic transformation and the shape memory effect is studied experimentally. The mechanical response of the actuator cooled by running water is preserved when the duration of the excitation (activating) electric pulses decreases to 2 ms. High-speed activation is accompanied by a delay in the mechanical pulse in comparison with the excitation electric pulse. The minimum duration of the mechanical pulse, taking into account the delay, was 8 ms, which corresponds to a frequency of 125 Hz with periodic activation. Estimates show that the delay time includes both the time of mechanical inertia and the time of thermal inertia associated with heat transfer. The possible limitation of the rate of activation due to kinetic phenomena during the thermoelastic martensitic transition is evaluated.

DOI: 10.1134/S1063783418060057

1. INTRODUCTION

Since the discovery of thermoelastic martensitic transformation in intermetallic alloys and the shape memory effect associated with it, attempts have been made to use final control elements based on them to create various mechanical systems, in particular, motors and actuators [1–6]. An attractive feature of such alloys is significant thermally controlled deformations. In particular, in a TiNi alloy under the effect of mechanical stress of the order of 100 MPa, deformations up to 8% can accumulate upon cooling as a result of the transition from the austenitic high-temperature phase to the low-temperature martensitic phase and completely disappear upon heating. Alloys with the shape memory effect applied as an engine working fluid, in comparison with other types of functional materials, have such advantages as high developing force, high specific power, and low heating required for activation. Among their shortcomings, the low rate of response is often mentioned, which is mainly explained by the need to wait for the time necessary to cool the actuator with the shape memory effect. To overcome this drawback, such approaches as forced convection of cooling air [7], the use of a heat sink [8], and cooling using a water channel [9] or a heat pump [10] were used. One of the best results that have been achieved so far is the response rate of a 35-Hz bending actuator based on thin wires of a Ti–Ni composite in a polymer matrix [11]. In addition to the use of them in applications, an experimental study of fast acting actuators with the shape memory effect should shed light on the physical laws governing the kinetics of the occurrence of a thermoelastic martensitic phase transition of the first order and the interrelationship of thermal and mechanical processes during the transition.

2. SAMPLES AND METHODS

A rapidly quenched ribbon of Ti_2NiCu alloy with the shape memory effect was selected as an object of research. Investigations of the structural and thermomechanical properties of this alloy were carried out by many researchers [12–20]. The original ribbons obtained at the melt cooling rates of approximately 10^6 K/s have an amorphous structure. The amorphous ribbon should be heat treated to obtain a crystalline phase and the shape memory effect. In the crystalline state, the alloy exhibits a thermoelastic martensitic transition of the first order from the austenitic phase B2 with a cubic lattice to the martensitic phase B19 with a monoclinic lattice. The temperatures of the beginning and the end of the forward and reverse mar-

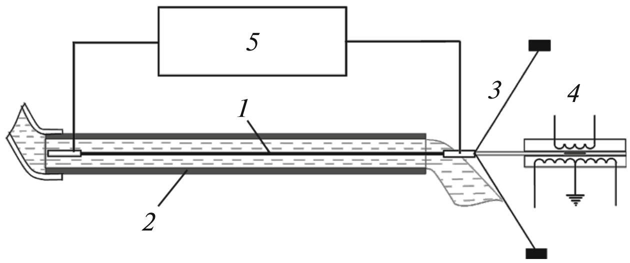

Fig. 1. Schematic diagram of the experimental setup for studying the activation of a rapidly quenched ribbon of Ti_2NiCu alloy with a thermoelastic martensitic transformation by pulses of electric current: (*1*) sample of a rapidly quenched ribbon of Ti_2NiCu alloy, (*2*) tube with running water, (*3*) string, (*4*) displacement sensor, and (*5*) current pulse generator.

tensitic transitions are M_s = 60°C, M_f = 52°C, A_s = 55°C, and A_f = 64°C, respectively [12]. The heat treatment can be carried out by heating in a furnace or by passing an electric current. The latter method has the advantage of more accurate control of the proportion of the crystalline phase, requires less energy, and does not require cumbersome equipment [21]. Namely the annealing by electric current was selected for the heat treatment of the ribbons for the experiments described below. When the current was passed, the phase composition of the ribbons was monitored by the electrical resistivity, as described in [22]. After annealing, a small part (approximately 1 cm) of the ribbon was placed in a special installation to measure the magnitude of the reversible deformation, depending on the temperature of the sample at various values of mechanical stress. A typical example of such dependence is described in [23]. This dependence is characterized by a sharp decrease in the strain during heating and an increase in cooling upon passage through the phase transition points, accompanied by a hysteresis. The difference in strain values in the martensitic and austenitic states is called reversible deformation. The reversible deformation has a nonmonotonic dependence on the applied mechanical stress: with increasing stress, the value of the reversible deformation first increases, after which its value decreases.

In the present study, the reverse martensitic transition in a rapidly quenched crystalline ribbon of Ti_2NiCu alloy from the martensitic phase to the austenitic phase was achieved by heating by pulses of electric current, and the forward martensitic transition was implemented by cooling the sample of the ribbon with a flow of cold water. The experimental setup is schematically presented in Fig. 1. Sample *1* was a section of a rapidly quenched ribbon of Ti_2NiCu alloy with length L = 30 cm, width b = 2 mm, and thickness h = 40 μm. It is fixed at one end in a tube with running water *2*, and its other end is attached outside the flow of water to string *3*, which creates a tension force. The string is used as an elastic element to reduce the mechanical inertia of the entire system. An LDVT S5-200AG inductive linear displacement transducer *4* is rigidly attached to the same end of the sample. It serves as a transformer converter, to which an alternating carrier signal of 5000 Hz is supplied. The amplitude of the signal at the output of the transformer is proportional to the movement of the rod rigidly connected to the actuator (ribbon), spring-loaded with the tensioned string. The range of measured movements is 0–5 mm. The signal from the sensor is transferred to the ADC (E14-440) and then to the computer. Contact lobes are soldered to the ends of the ribbon, which are connected to the current pulse generator *5*. Based on the data coming from the ADC to the computer, the strain rate of the sample is plotted, and the start and end of the excitation current pulse are recorded.

3. EXPERIMENTAL RESULTS

Initially, sample *1* is in a flow of flowing cold water in a martensitic state at a temperature T = 18°C below M_f. It experiences a tensile force up to 10 N from the tensioned string *3*. The mechanical stress created in the sample is in the range from 0 to 125 MPa. In the course of the experiment, a square-wave current pulse is fed from generator *6* with an amplitude of 1 to 40 A and a duration of 1 to 10 ms. As a result, the sample is heated by the Joule heat of the flowing current to temperature A_f. This causes a reverse martensitic transition of the alloy from the martensitic phase to the austenitic one and leads to a reduction in the length of the ribbon by 1–3%. After the current pulse ends, the running water quickly cools the sample below temperature M_f, and the ribbon returns to its original size.

The relative deformation of the ribbon versus time for different duration and amplitude of the current pulses is shown in Figs. 2a–2c. In the graphs, the dot-and-dash vertical lines show the moments of the beginning and the end of the current pulse.

Figure 2a demonstrates the mechanical response of the alloy sample to a current pulse of an amplitude of 17 A and a duration of 15 ms. There are four characteristic zones in the dependence curve: the initial delay is 6.0 ms, the leading edge is 4.0 ms, the plateau is 6.6 ms, and the trailing edge is 10.0 ms. The change in the length of the sample ΔL is approximately 3 mm, which corresponds to a relative deformation of the ribbon of $\Delta L/L \sim 1\%$. When the current pulse duration is shortened to 7 ms (Fig. 2b), the plateau practically disappears, and the delay becomes 3.0 ms, the length of the leading edge is 3.0 ms, the trailing edge is 8.0 ms, and the maximum strain of the sample is 0.9%.

The minimum pulse at which the response of the sample was detected (Fig. 2c) has an amplitude of 38 A and a duration of 2 ms. The following characteristic zones are observed in the response curve: the

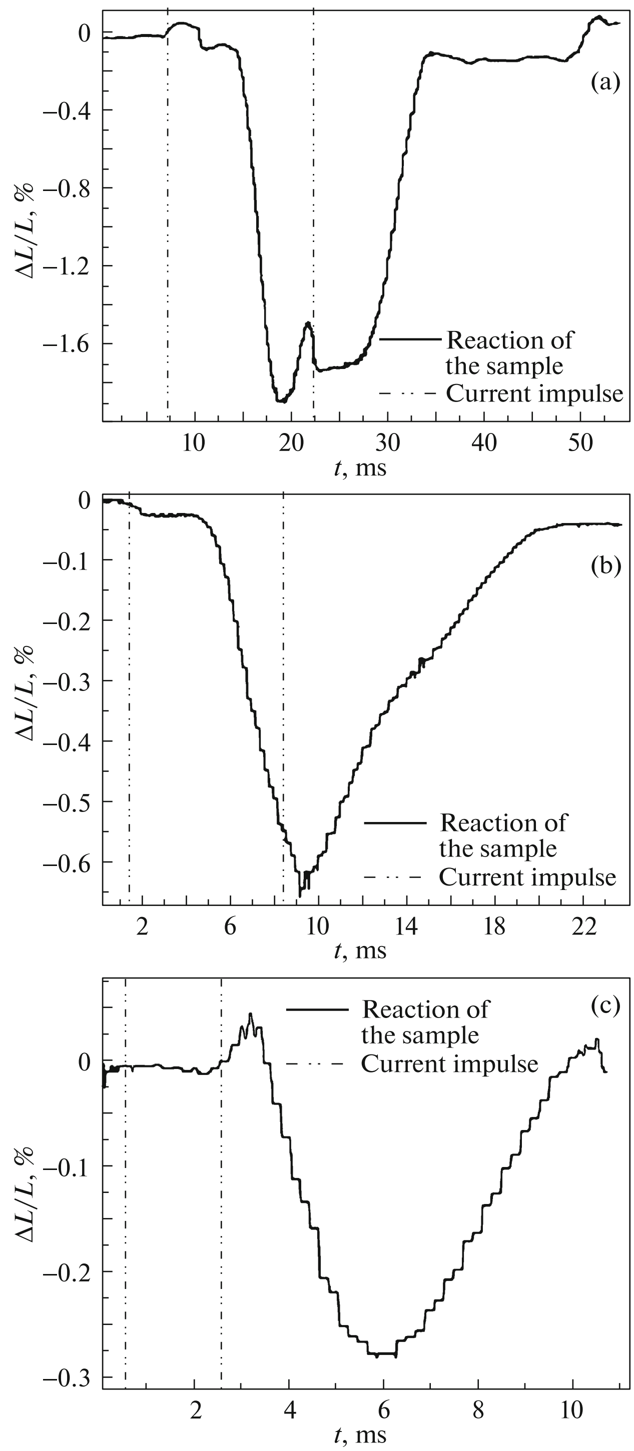

Fig. 2. Dependence of the ribbon deformation on time under activation with a single pulse of electric current with different duration and amplitude: (a) 15 ms, 17 A; (b) 7 ms, 17 A; and (c) 2 ms, 38 A.

delay is 2.3 ms, the response front length is 2.0 ms, and the trailing edge is 3.5 ms. In this case, the relative deformation of the sample is 0.3%, and the total response time considering the delay is approximately 8.0 ms. This corresponds to the oscillation frequency with periodic excitation of 125 Hz. The result exceeds the record for today value of the working frequency for the actuators with the shape memory effect [11].

4. DISCUSSION OF RESULTS

To make approximate estimates of the characteristic times associated with thermomechanical processes in the martensitic transition, we first evaluate the resonance frequency ω of the mechanical system, including a sample in the form of a ribbon, a rod of a displacement transducer, and a string. The measurements show that the total rigidity of the mechanical system is $\beta \sim 10^4$ N/m. The weight of the ribbon is small: $m_R = \rho Lhb \approx 0.15$ g, where $\rho = 6500$ kg/m^3 is the density of the alloy. The most massive moving part of the mechanical system is the displacement transducer rod; its weight is of the order of $m_s \approx 1$ g. Therefore, $\omega = (\beta/m)^{1/2} \approx 3 \times 10^3$ s^{-1}. The period of mechanical oscillations at resonance is $t_m = 2\pi/\omega \approx 2 \times 10^3$ s. The mechanical system of "sample–string–sensor" thus has a resonant frequency in the range of 10^2–10^3 Hz. This can limit the time of the initial delay zone, observed in all experiments, to the magnitude of the order of milliseconds. The initial delay also includes the time necessary for heating the ribbon to a temperature above A_s. Without taking into account the losses, time t_c necessary to heat the sample with an electric current above A_f can be estimated using the relation of $t_c \sim c\rho Lhb\Delta T/I^2R$, where $R = 6.5\ \Omega$ is the electrical resistance of the sample, $I \approx 100$ A is the current amplitude, $\Delta T = A_f - T_0$, T_0 is the water temperature, c is the specific heat, and ρ is density. Such an estimate gives the value of $t_c \sim 1$ ms, which coincides in order of magnitude with the times of mechanical inertia.

It is also necessary to estimate the possible contribution of characteristic times associated with the martensitic phase transition to the formation of the mechanical response of the system. The experimental data show that the alloy with the shape memory effect is characterized by a delay in the mechanical response with respect to the current pulse. This behavior is most clearly manifested under the shortest current pulses. In the case of a current pulse duration of shorter than 2 ms, the mechanical pulse begins after the end of the current pulse, and its termination is observed after 8 ms, including 2 ms of the initial delay (Fig. 2c).

We estimate the characteristic times necessary for the relaxation of a thermal pulse caused by an electric current. If the thermal resistance at the boundaries of the sample ribbon with running water is neglected, then, without taking into account the phase transition, the characteristic time is $t_1 \sim h^2/4a^2$. Here, h is the sample thickness, $a^2 = k/c\rho$ is the thermal diffusivity of the alloy, and k is the thermal conductivity coefficient. The estimation for Ti_2NiCu alloy at $k = 10$ W/(m K) and $c = 836.8$ J/(kg K) gives $t_1 \approx 0.04$ ms.

The presence of a phase transition slows the motion of the thermal front. The effect of the phase transition was taken into account using the solution of the Stefan problem [24]. To estimate the velocity of the thermal front considering the motion of the boundary of the first-order martensite–austenite phase transition, according to [24], the effective thermal diffusivity α is introduced, which is determined by the equation of $x = \alpha t^{1/2}$, where $x(t)$ is the coordinate of the phase transition boundary moving in the sample cooling, and t is time. Coefficient α is calculated using the known characteristic constants of the material, including the latent heat of the phase transition $\lambda =$ 10 kJ/kg and the temperature difference $\Delta T = M_f - T_0$. Using the method described in [24], we find that $\alpha \sim 10^{-3}$ m/s$^{1/2}$. Since the sample of the ribbon cools symmetrically on both sides, we obtain for the time of motion of the front of the phase transition by a distance of $h/2$ equation $t_2 = x^2/\alpha^2 \sim 10^{-4}$ s.

Thus, the thermal conductivity of the alloy, even taking into account the phase transition, does not explain the observed characteristic pulse delay times of the order of 6–8 ms. Only two unaccounted factors can explain this significant (by one to two orders of magnitude) divergence: heat transfer into running water and characteristic times of internal processes accompanying the martensitic phase transition. Indeed, estimates for the characteristic heat transfer time from a metallic sample to running water can give a relaxation time closer to the experimental values. Let us assume γ is a heat transfer coefficient of the ribbon to running water. At a water flow rate of the order of meters per second, the estimates, according to [25], yield $\gamma \sim 2 \times 10^3$ W/(m^2 K). For the thermal relaxation time t_3 without taking into account the phase transition, we obtain $t_3 = c\rho h/2\gamma \sim 5$ ms. The values obtained agree with the experimental results in the order of magnitude. The only factor that remains unaccounted for is the characteristic times associated with the thermoelastic martensitic transformation, in particular, the times necessary for the appearance of the nuclei of the martensite phase in the austenite with a sharp decrease in temperature and their growth. If the contribution of these processes is significant, it is less or comparable in the order of magnitude with the value of $t_3 \sim 5$ ms found above. This corresponds to the velocity of the austenite–martensite boundary at least $\nu = 10^{-2}$ m/s. At present, there are no results in publications on direct measurements of the characteristic rates of the martensitic transition under the thermoelastic martensitic transition in intermetallides. At the same time, the possibility of the motion of the martensitic (nonthermoelastic) transition boundary in steel at a velocity of the order of the sound velocity ($\nu \sim 10^3$ m/s) is reported [26]. The experimental estimate obtained in this paper enables us to assume that the limiting velocity of the austenite–martensite boundary in a forward thermoelastic transition in Ti_2NiCu alloy is more than 10^{-2} m/s.

The values of the activation rate of 8 ms for the duration of the pulse and 125 Hz for the periodic responses, achieved in these studies, are superior to the achievements of other authors on the response rate for actuators with the shape memory effect [11]. Specific power of the actuator based on a rapidly quenched ribbon of Ti_2NiCu alloy with the thermoelastic martensitic transformation, estimated by the equation of $P = F\Delta Lf/m_R$ ($F = 10$ N is the generated force, f is frequency, and m_R is weight), is relatively large ($P \sim 30$ kW/kg). We can assume that the principle of high-speed activation of rapidly quenched alloys with thermoelastic martensitic transformation and the shape memory effect in the form of ribbons, considered in this paper, despite the need for cooling with running water, is rather useful, for example, in underwater acoustics for generation of powerful acoustic pulses.

5. CONCLUSIONS

In conclusion, we formulate the main results of this paper.

(1) Study of the actuator based on rapidly quenched Ti_2NiCu alloy with the thermoelastic martensitic transformation, cooled with flowing water, showed that the mechanical response of the actuator is retained while reducing the duration of the excitation (activating) electrical pulses to 2 ms. High-speed activation is accompanied by a delay in the mechanical pulse in comparison with the excitation electric pulse. The minimum duration of the mechanical response, taking into account the delay, was 8 ms, which corresponds to a frequency of 125 Hz with periodic activation.

(2) Estimates of the characteristic times of thermal processes during activation, including the effect of the phase transition on the velocity of the thermal front, based on the solution of the Stefan problem, showed that the delay in the mechanical response is determined mainly by the intensity of heat transfer into running water.

(3) An experimental estimate is obtained for the limiting velocity of the austenite–martensite boundary for a direct thermoelastic martensitic transition of the first order in Ti_2NiCu alloy, which exceeds 10^{-2} m/s.

ACKNOWLEDGMENTS

The work was supported by the Russian Science Foundation, project no. 17-19-01748.

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Translated by O. Zhukova