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ACOUSTIC PROPERTIES OF TiNi-BASED ALLOYS

V. É. Gyunter, V. I. Chernyshev, and T. L. Chekalkin

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The specific features of the change in the acoustic properties of TiNi-based alloys are studied in a broad temperature interval. It is shown that in the temperature range of loading-induced martensite transformations, there is a region of long-term and small-amplitude low-frequency sound oscillations. The method of Fourier analysis is used to determine the frequency–amplitude characteristics of quasiperiodic oscillatory processes in TiNi-based alloys. In the temperature interval considered, the free low-frequency oscillations of the TiNi-based sample are characterized by a low level of damping.

Alloys with form memory are widely used for solving many technical problems and in medicine. In using TiNi-based alloys as materials (implants) implanted into an organism, they are subjected to the sign-variable action from the side of the organism and the ambient medium, and oscillations are excited both in the organism tissues and the implant material [1]. The phase transitions in TiNi-based alloys exert a strong effect on the physicomechanical properties in a broad temperature interval. Depending on the composition of TiNi-based alloys and their thermomechanical treatment, the acoustic properties of these alloys are characterized by a number of unusual phenomena [2–4]. In this study, we deal with the specific features of the changes in the acoustic properties of TiNi-based alloys near the temperature interval of martensite transformations.

The samples were fabricated in the form of tuning forks made from a TN-10 alloy. They were made from 0.5-kg ignots obtained in an induction furnace by remelting spongy titanium, N1-grade nickel, molybdenum, and iron. The ingots were partially subjected to sheet rolling at temperatures of $T = 1073$–1173 K up to $14 \times 20 \times 110$ mm dimensions; after that, the electroerosive method was employed to cut the samples from the ignots. To remove the cold-work roughness, the final annealing was carried out in vacuum (10^{-3} Pa) at $T = 1123$ K for 1 h. To determine the characteristic martensite-transformation temperatures with the use of the positions of martensite points (M_s, M_f, A_s, A_f, and T_R) [1], the temperature dependence of the electroresistance of the alloy was measured.

The acoustic characteristics of the samples were examined by means of an experimental setup for studying the change in the acoustic properties of the material depending on the test temperature. This method does not introduce additional perturbations into the oscillatory system, allowing one to fix reliably the oscillatory process in the samples at different temperatures. A study of transverse waves in a sample with independent external excitation and piezoelectric registration of free oscillations forms the basis of this method. The oscillations in the sample were recorded by a highly sensitive microphone whose frequency band coincides with the frequency range of oscillations in the sample determined with an oscillograph. After that, the analog signal was fed at the entrance of an amplifier; being amplified, it arrived at the entrance of the analog-to-digital converter of a PC. The digital signal was further Fourier-transformed by analyzing the behavior of the maxima of the entropy as is done in [5].

Sign-variable deformation is an action on the units of structures with form memory which occurs

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frequently in practice. Depending on the state of a material, deformation can occur either in the single-phase martensite (B19′ structure) state or in the two-phase (R + B19′ or B19′ + B2) state, or in the single-phase state B2. However, it is noteworthy that the sign-variable deformation of the state B2 near the temperature of the point M_s differs from the phase state B2 near the point M_d.

Gyunter et al. [6] considered the mechanism of sign-variable deformation of a TN-10 alloy at $T = 309$ K. It is established that, for $T > T_{M_s}$, the deformation is associated with the B2 → B19′ transition. With the load released, a portion of the martensite B19′ is preserved, thus causing residual deformation. The response of the martensite to inverse-sign cycling deformation leads to a B19′ → B2 transition, i.e., the material returns to the initial state under the action of stress. The mechanism of accumulation and return to deformation under the sign-variable action in this state does not cause significant changes in the structure of the alloy. This analysis of sign-variable deformation is correct for fairly low deformation velocities. In cases where the system participates in fast oscillatory processes, the deformation being insignificant and the rate of sign-variable action being significant, the deformation mechanisms have some specific features.

Being disturbed from equilibrium, any atomic system, including a TiNi-based alloy, that is in the premartensite state must get into equilibrium or another state if several stable states correspond to the specified conditions. The transition of the TiNi system from state B2 to state B19′ constitutes a complete oscillatory cycle. Here the scattering of the oscillation energy is determined by the set of relaxational processes occurring upon periodic deformation of crystals of the phase B2 and the martensite B19′. Therefore, it is impossible to determine the state of the system in the general form. It is necessary to take into account that one determining factor of the martensite reaction is heat release. According to the data of [1], the amount of heat released during the B2 → B19′ transition is greater than 8.3 kJ/mole. The same amount of heat is absorbed by the system during the reverse transition. The thermal conductivity of TiNi is extremely small and is 1 W/(m · K) [1]; therefore, the thermal processes for this alloy play a decisive role for oscillations, especially if the latter occur under adiabatic conditions (when the reaction heat is removed to the ambient medium).

Under loading, as soon as the martensite phase appears at $T > T_{M_s}$, the parameters of the system are described by the following relation [7]: $\Delta\sigma = \Delta H \Delta T/(T_0 \varepsilon_{\mathrm{m}})$, where $\Delta\sigma$ is the applied stress, ΔT is the change in temperature, $T_0 = (T_{M_s} - T_{M_d})/2$ is the temperature of the phase equilibrium, ΔH is the latent heat of transformation, and ε_{m} is the strain owing to the martensite reaction. For an individual ith martensite plate or a high-temperature phase microregion, the equation has the form [7]

$$\Delta\sigma_i = \pm\frac{\Delta H_i \Delta T_i}{T_{0i}\varepsilon_{M_i}}. \tag{1}$$

Here the plus and the minus correspond to heat release and absorption, respectively.

However, if the appearance of a single ith martensite plate is caused by application of the load $\Delta\sigma$, the increase in temperature by the quantity $\Delta T_i'$ results in the appearance of an opposite sign [7]:

$$\Delta\sigma_i = \frac{\Delta T_i' c \varepsilon_{M_i} \Delta T_i'}{T_{0i}\varepsilon_{M_i}}, \tag{2}$$

where c is the specific heat.

Equating expressions (1) and (2), one can obtain conditions for an oscillating system (disregarding other relaxational processes):

$$\frac{(\Delta T_i')^2 c}{T_{0i}\varepsilon_{M_i}} = \frac{\Delta H_i \Delta T_i}{T_{0i}\varepsilon_{M_i}}, \qquad (\Delta T_i')^2 = \frac{\Delta H_i \Delta T_i}{c}.$$

Under the condition $\Delta T_i' = \Delta T_i$, we obtain

$$\Delta T_i' = \pm\frac{\Delta H_i}{c}.$$

This expression determines the equilibrium of the system under adiabatic conditions, when the release of the latent heat of transition causes the local heating or, as a consequence, the appearance of a thermal

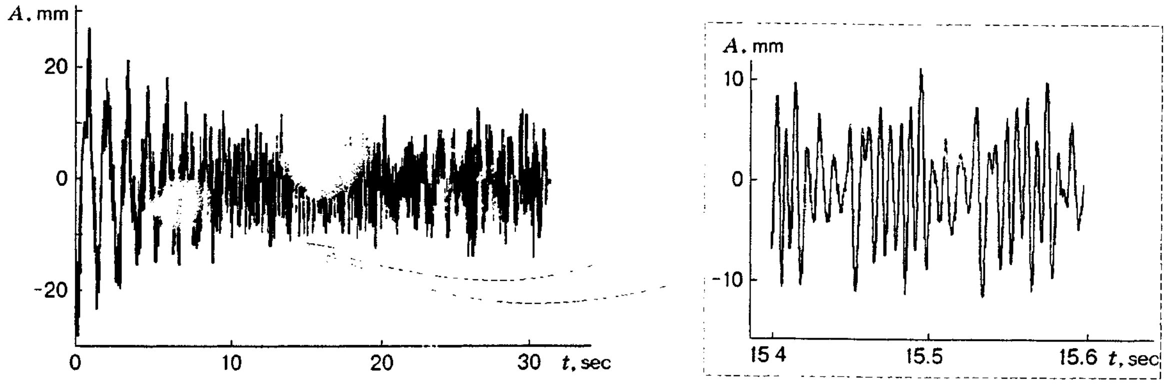

Fig. 1. Amplitude–time dependence of free oscillations of the TN-10 sample.

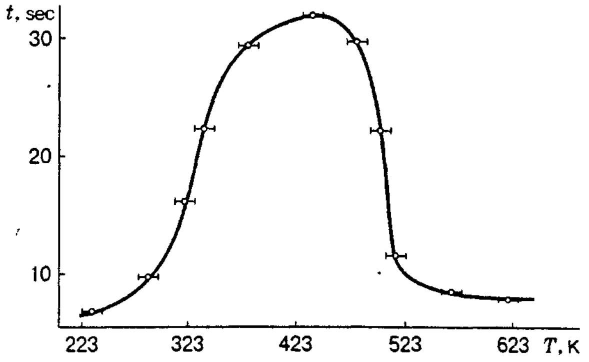

Fig. 2. Temperature dependence of the duration of the sample oscillations.

front, which is the "propulsing" force of the reverse transition. One can expect that in initiating low-frequency oscillations of the TiNi-based sample in the temperature interval in which the martensite state can possibly occur upon load, i.e., at $T_{M_f} \leqslant T \leqslant T_{M_d}$, the oscillations are characterized by longer damping (the sound range of frequencies).

Figure 1 shows the amplitude–time dependence of the oscillations of a TN-10 tuning fork at 423 K. In the initial period, the oscillations are quasiharmonic; note that the oscillation amplitude varies almost according to a logarithmic law. Beginning with a certain moment, the oscillation amplitude remains almost constant, and the period of oscillations decreases. One can observe the characteristic pulsations during the entire period of the oscillatory process. The oscillatory system behaves as if the driving force supported oscillations during a long period. The stability of the oscillation frequency and the presence of pulsations indicate that the frequency of the driving force is near one of the lowest harmonics undergoing phase shear at a small angle.

In examining the amplitude–time dependence of the free oscillations of a TN-10 sample (Fig. 1), results indicating that the thermal effects are one determining factor of the martensite reaction were obtained. In the interval of temperatures $T_{M_f} \leqslant T \leqslant T_{M_d}$, one can observe an increase in the duration of the oscillations of the system, whereas the oscillations are almost completely suppressed in the martensite state. Figure 2 shows the temperature dependence of the duration of the oscillations. The distinctive feature of this dependence is the existence of a broad temperature interval, in which the duration of the low-frequency oscillations of small amplitude is large (the primed points characterize the accuracy of temperature determination). The emergence of this region is due to the sign-variable action upon initiation of the external stress of martensite reactions in a two-phase state.

Thus, the oscillatory system made of a TN-10 alloy has an anomalously large duration of oscillations in the temperature interval $T_{M_f} \leqslant T \leqslant T_{M_d}$, i.e., in the range of appearance of a two-phase state upon stress.

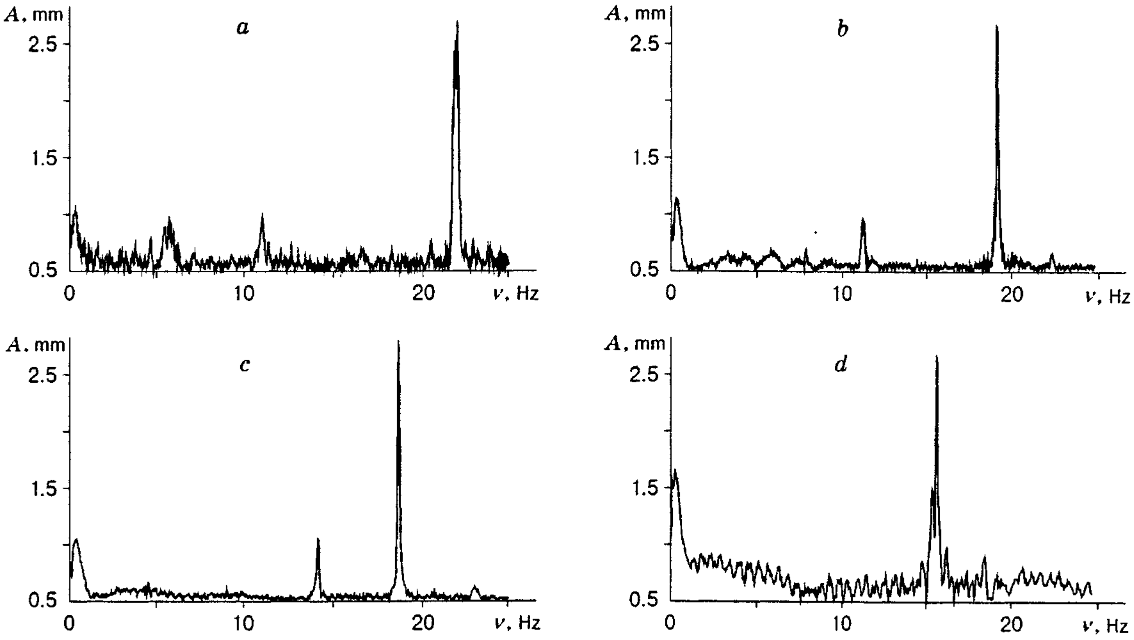

Fig. 3. Amplitude–frequency dependence of the free oscillations of the TN-10 sample for T = 423 (a), 323 (b), 273 (c), and 223 K (d).

An analysis of the amplitude–frequency dependence performed in accordance with [5] gives additional information. For high temperatures, in the interval of low frequencies ν = 0–25 Hz there are many peaks (Fig. 3a). With the temperature decreased to T = 323 K, two low-frequency peaks at frequencies of $\nu \approx 11$ and 19 Hz are distinctly seen on the diagram (Fig. 3b). As the temperature further decreases, the peaks approach each other, merging for $T = T_{M_f}$ (Fig. 3c and d). The amplitude–frequency peaks are absent below this temperature. This behavior of the curve $A(\nu)$ makes it possible to assume that a different number of martensite and high-temperature phase domains (having, as is known, a plate-like morphology) participate in the oscillatory process, thus contributing to it; these domains are divided into classes or groups (depending on the dimensions, volume, and structural and morphological specific features).

The process considered is characterized by the mechanism of oscillation damping in TiNi-based alloys, i.e., high mobility of the interfaces (of the martensite and high-temperature phases) and a large value of the transformation enthalpy, which results in the presence of a thermal front for a low-conductivity alloy.

The effect of the "undamping" region of low-frequency sound oscillations of small amplitude has been shown on metal systems; this opens up the possibility of creating devices with new properties.

REFERENCES

1. V. É. Gyunter, G. Ts. Dambaev, P. G. Sysolyatin, et al., *Medical Materials and Implants with Form Memory* [in Russian], Izd. Tomsk. Univ., Tomsk (1998).
2. W. J. Buehler and R. C. Wiley, "The properties of TiNi and associated phases," Report NOLTR 61-75 (AD 266607), U.S. Naval Ordnance Lab., Aug. 3 (1961).
3. R. R. Hasiguti and K. Iwasaki, "Internal friction and related properties of TiNi intermetallic compounds," in: *Proc. of the Symp. on TiNi and Associated Compounds*, U.S., Naval Ordnance Lab., NOLTR 68-16, Dec. 20 (1968), pp. 401–412.
4. D. Bradley, "Sound propagation in near stoichiometric TiNi alloys," *J. Acoust. Soc. Amer.*, **37**, 700–704 (1975).

5. V. T. Sarychev, *Spectral Estimation by the Methods of Maximum Entropy* [in Russian], Izd. Tomsk. Univ., Tomsk (1994).
6. V. É. Gyunter, A. N. Matyunin, and L. A. Monasevich, "Deformation cyclostability of medical alloys with form memory," in: *Implants with Form Memory* (collected scientific papers) [in Russian], No. 1, 42–44 (1993).
7. V. É. Gyunter, V. V. Kotenko, M. Z. Mirgazizov, et al., *Alloys with Form Memory in Medicine* [in Russian], Izd. Tomsk. Univ., Tomsk (1986).