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Modeling of Ultrasonic Initiation of Shape Memory Effect

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Modeling of ultrasonic initiation for alloys with shape memory effect is carried out. The ultrasonic heating process is described taking into the account the temperature dependence of the studied material properties. Research process of heat generation for the TiNi samples under the ultrasonic influence shows that the treatment of the material under the localized acoustic influence causes the constant temperature distribution along the sample. It is possible to control the phase transformation in the material, the speed of its implementation by varying the frequency and amplitude of the ultrasonic vibrations during the phase transition. The aim of this study is the modelling heating of alloys with shape memory effect under ultrasonic action at several resonance frequencies.

Keywords heat treating, modeling processes, phase transformation, shape memory effect, TiNi alloys, ultrasonic influence

1. Introduction

Materials and shape-memory alloys (SMAs) have attracted attention since the discovery and the first publication of Chang and Reed in 1951 (Ref 1). Among these materials, shape memory alloys exhibit extremely large inelastic, recoverable strains (of the order of 10%), resulting from the transformation between the austenitic and the martensitic phases. SMAs have been given a lot of attention mainly for their innovative use in practical applications. This property allows the use of SMAs in many innovative technical solutions. For example, SMA is used for actuators, composite systems with integrated fibers, acting as actuator in special systems for active control of dynamic and structural behaviors, etc.

Phase transformations are characterized by thermoelastic behavior and undergo at relatively low temperatures (typically up to 100 °C) for materials with shape memory effect (SME) in contrast to steel. TiNi-based shape memory alloys are characterized by damping effect which makes them a promising material for a controlled change of properties in a normal external medium, including the ultrasonic influence. Taking into account that the maximum damping properties take place in the implementation of the thermoelastic transition in SMAs, we should expect the highest energy absorption of acoustic vibrations in the temperature range of transformation.

As the display of shape memory effect is related to temperature and (or) mechanical stress influence (Ref 2), and they can operate simultaneously under ultrasonic influence, the ultrasonic vibrations (UVs) can initiate the recovery process in alloys with shape memory, i.e., thermoelastic phase transformation (Ref 3). Indeed, the ultrasonic vibrations can significantly increase the temperature of the material, which inevitably must initiate martensitic reactions due to dissipation of acoustic energy, i.e., ultrasound in this case is one way of heating. But the kinetics of the martensitic transformations is changed due to significant differences from other types of ultrasonic heating (Ref 4).

The excitation of acoustic vibrations of the low ultrasonic frequency range in the material leads to the dissipation of sound energy which is irreversibly transformed into heat. The ultrasonic heating can be unsteady along the sample and rather large, up to the melting temperature (Ref 5). The dissipation of elastic energy of the ultrasonic wave takes place at high intensity of ultrasound, the increase of the damping factor occurs, which is associated with the coefficient of internal friction of the material. The resonant frequency of the ultrasonic influence is changed; the acoustic parameters of the system are redistributed. If the waveguide system is in the resonance regime, the distribution of the acoustic parameters in it is also constant. Since the heat release depends on the amplitude of deformation, the temperature distribution in the sample is described by the sine function, and heating is unsteady (Ref 5, 6).

In TiNi-based alloys in the temperature range of martensitic transformations alternating strain at a constant temperature also leads to a reversible form change due to changes in the transition B2 ↔ B19′ under load (Ref 2).

2. Formulation

Converting the maximum amount of energy of ultrasonic waves into heat will occur when the systems are in the resonant regime. This regime is characterized by the sinusoidal distribution of the acoustic parameters along the waveguide length. In order to build a model for the investigated processes it is

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convenient to choose the rod of the resonant length, fixed to the concentrator of the longitudinal ultrasonic vibrations.

The system can be described by the following set of equations:

$$
\begin{aligned}
&\frac{\partial^2 T_1}{\partial x^2} - \frac{1}{\chi_1}\frac{\partial T_1}{\partial t} = -\frac{E\varepsilon_{m0}^2 Q^{-1} f}{2a_1}\sin^2 k(l-x), \quad 0 \le x \le l;\ t>0;\\
&\frac{\partial^2 T_2}{\partial x^2} - \frac{1}{\chi_2}\frac{\partial T_2}{\partial t} = 0, \quad -\infty < x \le 0,\ t>0;\\
&a_1\frac{\partial T_1}{\partial x} = a_2\frac{\partial T_2}{\partial x};\ T_1 = T_2, \quad x=0,\ t>0; \qquad \text{(Eq 1)}\\
&a_1\frac{\partial T_1}{\partial x} = 0, \quad x=l,\ t>0;\\
&T_2 = T_0, \quad x \to -\infty,\ t>0;\\
&T_1 = T_2 = T_0, \quad -\infty < x \le l,\ t=0.
\end{aligned}
$$

where T_1 and T_2 are the temperature of the rod and the concentrator, respectively; T_0 is the initial temperature of the rod; $\chi_{1,2} = \frac{a_{1,2}}{\rho_{1,2}c_{1,2}}$ is the temperature coefficients of conductivity; $a_{1,2}$ is the heat conductivity; $c_{1,2}$ is the specific heat; $\rho_{1,2}$ is the densities; $\varepsilon_{m0} = \xi_{m0}k$ is the deformation amplitude at the antinode; ξ_{m0} is the amplitude of displacement at the free end of the rod; f is the oscillation frequency; E is the modulus of elasticity; Q^{-1} is the internal friction, l is the sample length; x is the displacement relative to the beginning of the sample; t is the time of ultrasonic influence, temperature conductivity; k is the wave number.

Using the Laplace transform we can give the solution to the system (1), describing the temperature increase at any given time, neglecting the heat exchange with the medium and heat dissipation in the concentrator.

$$
\begin{aligned}
\Delta T(x,t) &= T - T_0\\
&= \frac{Q^{-1}E\xi_{m0}^2 f}{256a_1}\Big\{48k^2\chi_1 t + \left(1 - e^{-16k^2\chi_1 t}\right)\\
&\qquad \times \cos 4k(l-x) - 16\left(1 - e^{-4k^2\chi_1 t}\right)\\
&\qquad \times \cos 2k(l-x)\Big\} \qquad \text{(Eq 2)}
\end{aligned}
$$

The phase transformations cause a change of the physical and mechanical properties of the material (Young's modulus and specific heat). Consequently, the parameters in (2) are also functions of the temperature, which must be considered.

The materials, where the main deformation carriers are twin and martensitic transitions, have complex damping characteristics that depend on several factors. In all cases, near the phase transition temperature, a sharp change of internal friction occurs, and the damping constant may vary (Ref 7). The dependence of the specific heat and elastic modulus on the temperature of the material is presented in the following form (Fig. 1).

The high mobility of the phase boundaries and high value of enthalpy of the transformation determine the influence of the thermal front on the mobility of the interface with low thermal conductivity of the alloy. Since the wave speed in the medium is characterized by the Young's modulus, we should expect a change in the length of the ultrasonic wave with the temperature increase. This fact plays an important role in the analysis of accounting data.

The vibration energy absorption of TiNi alloy in the martensitic phase is caused by the movement of mobile interfaces (e.g., twin, phase boundary), which leads to a sharp increase of internal friction in the martensitic, and especially in two-phase states.

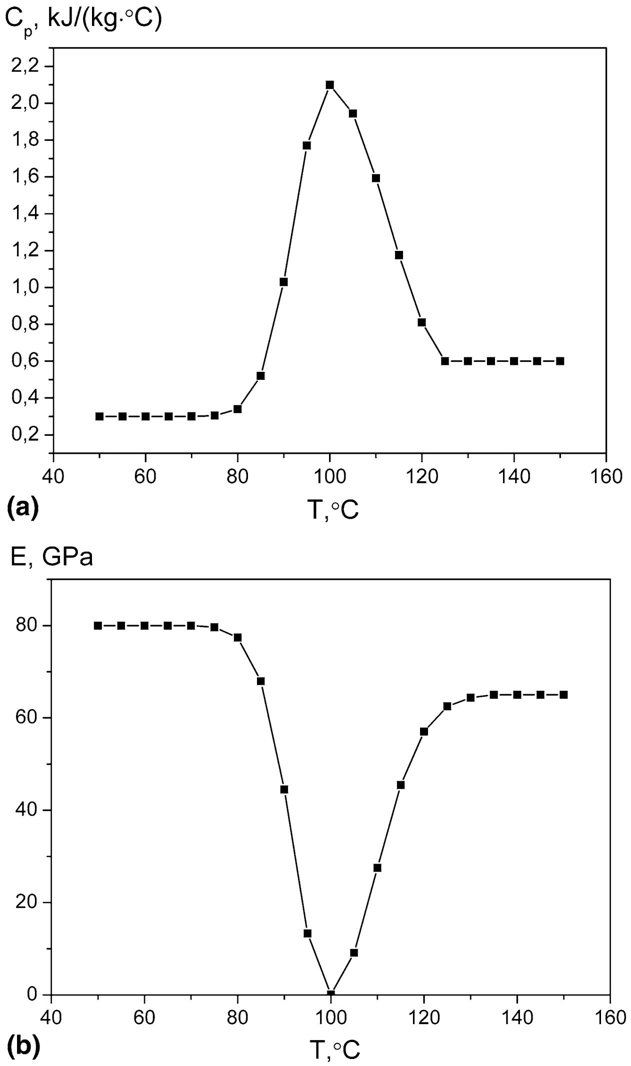

Fig. 1 Modeling dependence of specific heat and elastic modulus of TiNi upon heating

A significant growth of the decrement of vibrations in the range of transformations is associated with the influence of external or internal stresses on the temperature of formation and disappearance of different variants of martensite. Taking into account that the internal friction is much smaller in the high-temperature austenitic phase than in the martensitic one, we use the dependence of internal friction on temperature presented in Fig. 2.

3. Numerical Results and Comparison to Experiments

The dependence of the temperature on the insonation time is obtained for the samples of half-wave-length using a mathematical Maple apparatus (Fig. 3). Taking into account the above-mentioned factors at the model calculations the temperature of the waveguide is increased according to the nonlinear law (Fig. 4).

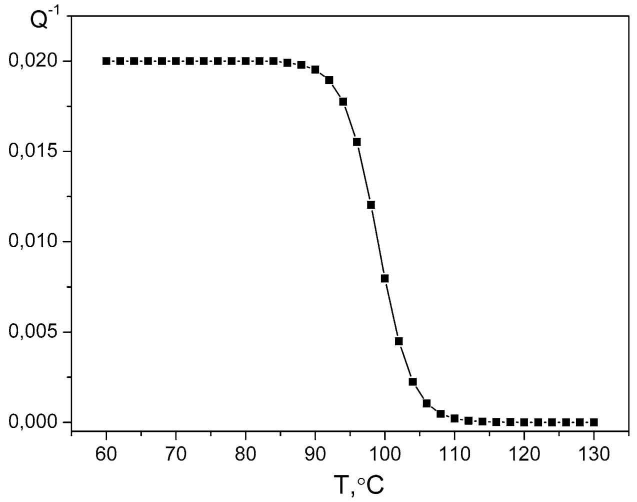

Fig. 2 The dependence of internal friction on the temperature

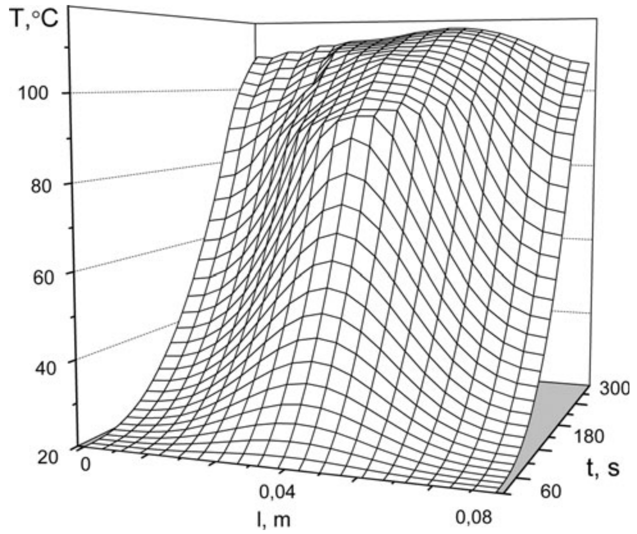

Fig. 3 Temperature profile for TiNi waveguide

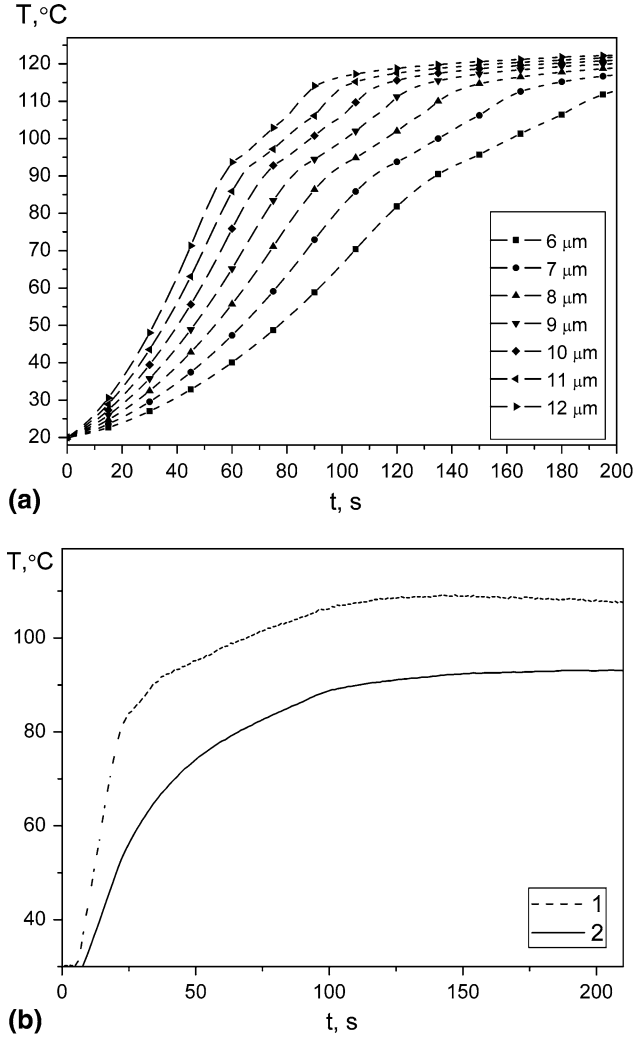

Fig. 4 The influence of the ultrasonic vibrations on the temperature change of TiNi waveguide: (a) calculated in the area of the maximum heating (b) experimentally calculated, the maximum (1) and the average along the sample (2)

There are three areas for the ultrasonic heating in the martensitic, two-phase and austenite states. The rate of change of the temperature of TiNi waveguide for these areas is different and ranged from 0.05 to 3 °C/s that is reflected on the waveguide temperature profile (Fig. 5) and characterized by different physical properties of the material.

Little information exists regarding the use of different methods for measuring temperature of bulk samples, especially under prolonged ultrasonic influence. The study of the sample temperature profile under the ultrasonic influence is performed using a thermal imaging system NEC TN9100. A thermal imager is a contactless high-resolution imaging camera, the spectral range of measurements vary from 8 to 14 μm. The correction for waveguide emissivity is performed by direct emissivity measurement to provide the true temperature values of the sample.

Ultrasonic generators with automatic tuning of the resonant frequency with converters of resonant frequency of 22 and 44 kHz are used to excite the ultrasonic vibrations. Built-in automatic system for maintenance of the resonance frequency provides work of the radiator in the resonant regime even when the parameters of load and the resonant frequency of the attached waveguides are significantly changed.

The thread connection is used to fix the cylindrical samples (waveguides) with a diameter of 10 mm and a length of 70 ÷ 80 mm to the concentrator. The thermal imaging camera is located at a distance of 0.30 m from the waveguide so that the whole sample and the end of the ultrasonic concentrator can be observed on a computer monitor. TiNi alloy is used as a sample where the direct and reverse phase transitions are realized by the scheme B2 → B19′ and the characteristic temperatures measured by differential scanning calorimetry, are: M_s = 72 °C, M_f = 46 °C, A_s = 85 °C, A_f = 114 °C.

Testing is defined by the following procedure. The system is supported in the resonance frequency corresponding to the natural frequency of the magnetostrictive transducer and the waveguide. The vibration frequency is continuously recorded by frequency meter. The amplitude is maintained constant by changing the power of the ultrasonic vibrations. The amplitude, the vibration frequency, the sample temperature, and the exposure time are measured during the ultrasonic influence.

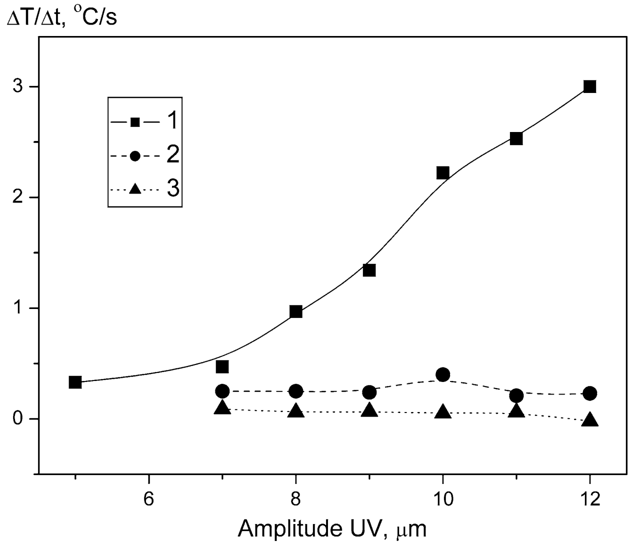

Fig. 5 The dependence of the experimentally calculated heat release intensity of TiNi waveguide on the amplitude of the ultrasonic influence 1—martensite, 2—two-phase state, 3—austenite

Thermal studies of the ultrasonic heating of TiNi waveguides show that the maximum heating is observed in the nodes of displacement and the minimum at the antinodes of displacement of mechanical vibrations for the resonant length samples under the ultrasonic influence. The sample of "wave" type is at a frequency of 44 kHz and the maximum heating takes place in two areas; the sample of "half-wave length " type is at a frequency of 22 kHz and the maximum heating in one area—in the middle (Fig. 6).

Localized acoustic influence on the material causes unsteady heating and the appearance of the permanent temperature distribution along the sample. The temperature drop is up to 30°. The energy dissipation is associated, on the one hand, with the movement of the phase boundaries during the growth of martensite crystals, on the other hand, with the need to overcome barriers of the martensite crystals nucleation of supercritical size (Ref 8).

The software of the thermal imaging system is used for the kinetics investigation of ultrasonic heating of TiNi waveguides both on the linear profile and assigned area of the sample. The temperature field is measured at a frequency of 1 Hz. The temperature difference along the sample in the martensitic and austenite phases is up to 20-30 °C upon heating due to the energy absorption of the ultrasonic vibrations. The ultrasonic vibrations do not cause further significant heating of the waveguide in the austenitic state and the temperature distribution along the sample is stabilized. This is due to significantly lower level of the internal friction typical for TiNi in the austenitic state, as compared with the martensitic and two-phase (Ref 2). The dissipation of acoustic energy in the austenitic state practically does not occur. However, over time, the heterogeneity of the temperature distribution along the sample is kept (Fig. 6). Figure 6 shows that the calculated and experimental data is in good agreement. The minor divergence between the curves can be explained by assumed presence of the temperature dependence of thermal-conductivity and also neglecting heat transfer to environment.

It should be noted that a non-linear increase of the waveguide temperature is observed depending on the time of the ultrasonic influence. This is associated with a significant change in the level of internal friction during the transition from the martensitic to the austenitic state and the energy absorption due to the endothermic phase transition of the first kind.

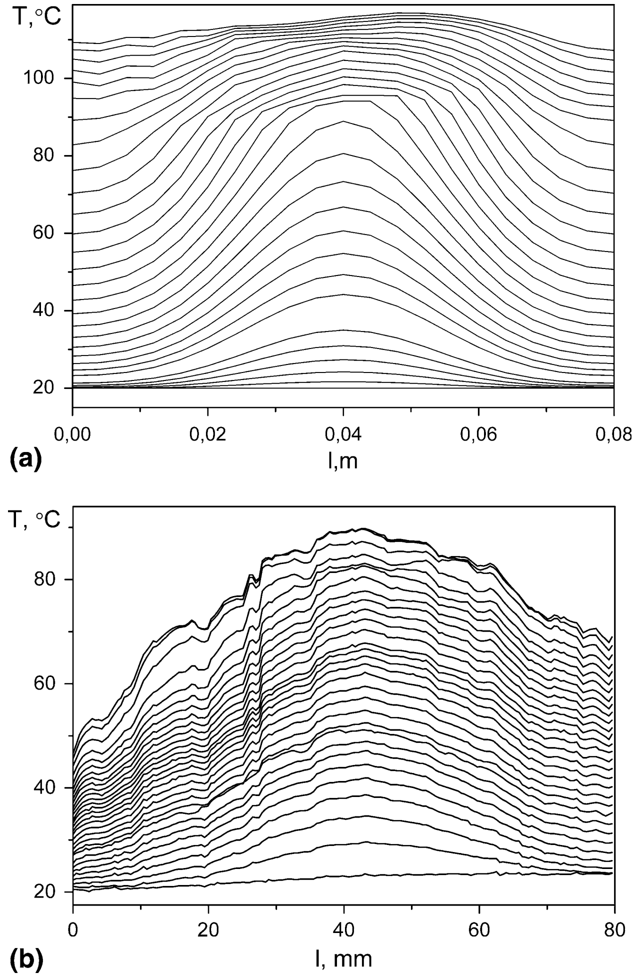

Fig. 6 The distribution temperature profiles along the sample with the interval of 5 s under the ultrasonic influence at a frequency of 22 kHz, (a) calculation, (b) experiment

While maintaining constant amplitude of mechanical displacements at the end of the waveguide, the maximum heating rate is observed when the material is in the low-temperature martensitic phase, and in our case is equal to 3°/s.

Figure 4(a) shows the dependence of the temperature of TiNi-waveguide in the area of maximum heating (node of ultrasonic mechanical displacements) on the time of the ultrasonic influence at the frequency of 22 kHz of varying intensity. Since the maximum heating takes place in the areas of the antinodes of mechanical stresses, the heating rate is determined in these places (Ref 9).

Phase transformation of the first kind begins in the material at a temperature of A_s = 85 °C which is associated with the energy absorption, the heating rate is decreased and equal to 0.1 °C/s. The transition of the material to the high-temperature austenitic state practically stops the process of heating, the temperature along the sample is stabilized, and the heating rate with the increases of vibration amplitude is not changed.

The phase transformations take place in TiNi alloy under the ultrasonic influence, which change the physical and mechanical properties of the material defining the speed of propagation of elastic waves, in particular, the Young's modulus. The ultrasonic initiation of shape memory effect in TiNi is accompanied by changes of the heating rate of the material and the acoustic parameters of the system. The change of the Young's modulus, and hence the propagation velocity of longitudinal ultrasonic waves in the thermoelastic phase transformation for the same waveguide system should lead to a redistribution (displacement) of nodal points of the standing wave., i.e., the displacement of maximum heating region of the waveguide should be observed in the process of ultrasonic initiation of thermoelastic phase transformation.

Indeed, the analysis of profiles of the temperature distribution along the sample under the ultrasonic influence at frequency of 44 kHz shows that the displacement in the point corresponding to the first maximum temperature takes place. The displacement for the TiNi sample of the wave length type is 6 mm and associated with a change of the resonant waveguide size due to the thermoelastic phase transformation and physical and mechanical property changes which determine the speed of propagation of ultrasonic waves. It should be noted that such behavior of the first maximum peak (its displacement) is predicted in modeling the processes of heat release in the TiNi under the ultrasonic influence. The speed change of ultrasonic in the sample causes the resonant frequency change of the system in a wide range, in addition to the redistribution of the nodal points of the standing wave. For example, the resonant frequency change for samples of half-wave-length is up to 4 kHz.

Analysis of the experimental dependence of the heat release intensity in the node of the sample on the temperature under the ultrasonic influence shows that the maximum heat release (from 2.0 to 2.5 °C/s) is observed in the range from 30 to 70 °C. The material undergoes reverse thermoelastic phase transformation in the same temperature range. The heat release rate decreases due to the transition of the material to the high-temperature austenitic state, and the samples are practically not heated.

In order to change the trajectory of operating actuating elements and decrease the time of the phase transition, ultrasonic initiation in the alloy is performed consistently at several resonant frequencies.

Moreover, the frequency is changed when the temperature at the stress antinodes of the material has reached the value of a reverse martensitic transformation finish temperature (A_f).

Practical implementation of the actuating element is the following. The ultrasonic vibrations are excited in the TiNi sample of the resonant length (or any other, having shape memory effect). The sample is locally heated due to the ultrasonic energy dissipation. Moreover, the maximum heating occurs at the points (Fig. 7a), corresponding to stress antinodes (the units of mechanical displacements).

The temperature is reached earlier in these areas before the end of the reverse martensitic transformation finish temperature (A_f). After the transformation of the material from the martensitic to the austenitic state (temperature range of A_s-A_f), further heating in these areas will not occur, since the ultrasonic energy dissipation in the material in the austenitic state practically does not take place (Fig. 7b). The other areas of the sample will be heated up as due to the absorption of acoustic energy, and due to the heat transmission from the hotter parts of the node till the temperature of A_f.

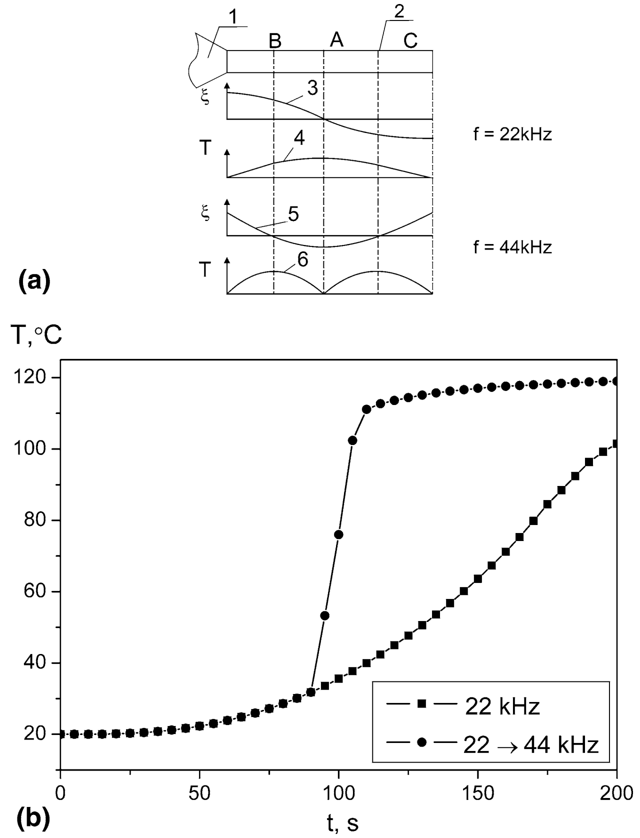

Fig. 7 The scheme of shape memory effect realization (a) and modeling of the temperature distribution along the waveguide in the center of the waveguide (b) at several resonance frequencies 22 + 44 kHz

Changing the resonant frequency of the ultrasonic vibrations, for example, from 22 to 44 kHz, when the temperature of A_f is reached at the nodal points, provides intensive heating of the sample in the new units of mechanical displacement, which leads to much faster initiation of shape-memory effect along the sample, i.e., achieve its heating to the temperature of A_f.

This method of ultrasonic heating of TiNi sample by successive changes of the vibration frequency can restore the pre-specified deformation at the nodal points that can be widely used in various clamps, actuators, etc.

Modeling of ultrasonic initiation of shape memory effect at two resonant frequencies shows that the rate of temperature change for TiNi waveguide has been reached 8 °C/s.

4. Conclusions

Using the energy of ultrasonic vibrations is new way to initiate the shape memory effect in alloys with thermoelastic phase transformations. Modeling of ultrasonic initiation for alloys with shape memory effect is carried out. These results can be used for predicting and modeling the phenomena associated with ultrasonic initiation of shape memory effect for actuating devices under ultrasonic influence.

Research process of heat generation for the TiNi samples under the ultrasonic influence shows that the treatment of the material under the localized acoustic influence causes the constant temperature distribution along the sample. It is possible to control the phase transformation in the material, the speed of its implementation by varying the frequency and amplitude of the ultrasonic vibrations during the phase transition.

The distinctive feature and advantage of this method of initiation is that one-sided access to the sample to implement the SME is required. The method can be widely applied in various clamps, actuators, etc.

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References

1. L.C. Chang and T.A. Read, Behavior of the elastic properties of AuCd, *Trans. Met. Soc. AIME*, 1951, **189**, p 47 (in English)
2. V.A. Likhachev, S.L. Kuzmin, Z.P. Kamentseva, Shape Memory Effect, Leningrad State University, Leningrad, 1987, p 216 (in Russia)
3. V.V. Klubovich et al., Generation of Shape Memory Effect in Ti-Ni Alloy by Means of Ultrasound/Shape Memory and Superelastic Technologies, *Proceedings II Intern. Conference, California, USA*, 2–6 March 1997, A. Pelton, Ed., Asilomar, California, 1997, p 59–64 (in English)
4. V.V. Rubanik, V.V. Klubovich, and V.V. Rubanik, Jr., The Ultrasounds Initiation of SME, *J. Phys.*, 2003, **112**(IV), p 249–251 (in English)
5. A.V. Kulemin, *Ultrasound and Diffusion in Metals*, Metallurgiya, Moscow, 1978 (in Russia)
6. R.B. Mignogna et al., Thermographic Investigation of High-power Ultrasonic Heating in Materials, *Ultrasonic*, 1981, **7**, p 159–163 (in English)
7. T.W. Duerig and A.R. Pelton, *Ti-Ni Shape Memory Alloys, Materials Properties Handbook Titanium Alloys*, ASM International, Materials Park, 1994, p 1035 (in English)
8. V.V. Rubanik, Jr., V.V. Rubanik, and V.V. Klubovich, The Influence of Ultrasound on Shape Memory Behavior, *Mater. Sci. Eng. A*, 2008, **481–482**, p 620–622 (in English)
9. V.A. Lihachev, *Materials with Shape Memory Effect*, Vol 4, St.-Petersburg, 1998 (in Russia)