Acousto- and electroplastic effects in alloy with reversible martensitic transformation

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Abstract. The article discusses the deformation behaviour of Ti₄⁹.₃Ni₅₀.₇ alloy in the austenitic state during tensile tests under pulsed current and ultrasound at ambient temperature and 200 °C. The stress jumps from a combination of ultrasound and / or single pulse current are analyzed. The direction and magnitude of stress jumps are determined by the phase state of the material, the degree of deformation and the presence of electroplastic (EPE) and acoustoplastic (APE) effects. The different direction of the stress jumps in this shape memory alloy is related to the position of the deformation temperature relative to the deformation martensite formation temperature.

1. Introduction

Modern materials in the process of production or operation may experience complex external effects of various natures, for example, associated with mechanical stresses and deformation, electromagnetic field, acoustic waves, and vibrations. The behaviour of materials in such difficult conditions requires an analysis of the influence of external factors on their physical and mechanical properties. The presence of structural phase transformation in materials imposes additional requirements on the prediction of technological and operational responses to external impacts. One of the strategic tasks in the process of production is to increase the deformability and reduce the effort in metal forming process, for example, when cold rolling or drawing long products of thin section.

In [1, 2], the effect of the joint use of Severe Plastic Deformation (SPD) and ultrasound (US) was demonstrated in pure nickel - reduction of flow stresses, relaxation processes and hardening of the material depending on the ultrasound amplitude. The combined use of SPD and pulse current also proved to be a method for improving technological and functional properties, as well as the microstructure of various materials: in TiNi alloy [3], in TRIP and stainless steels [4], in aluminum [5-7] and magnesium alloys [8].

In recent decades, the combined effect of various methods with the aim of obtaining the required technological and functional characteristics has been actively investigated. In pure copper [9] and
nickel [10] this possibility was shown by the example of the sequential application of ultrasound and pulse current, which led to an increase in the effect of a decreasing flow stresses.

At present time, a special role belongs to structural alloys with the shape memory effect Ti49.3Ni50.7, which can undergo thermelastic reversible martensitic transformations, both during production and during operation processes. A potential method of increasing the deformability of Ti49.3Ni50.7 alloys is the use of electroplastic (EPE) and acoustplastic (APE) effects [11-13], however, the mechanism of such influence is not sufficiently studied.

The purpose of this work is to investigate the electroplastic and acoustplastic effects during tension under pulse current and ultrasound in Ti49.3Ni50.7.

2. Material and methods

The object of the study was an alloy with shape memory effect in the austenitic state at ambient temperature Ti49.3Ni50.7 in the form of a wire with a diameter of $\varnothing$ 1.5 mm after quenching from 800 °C with a grain size of $\sim$ 50 μm. In accordance with the quality certificate, the start temperature of martensitic (Ms) and final temperature of austenitic (Af) transformations for the Ti49.3Ni50.7 alloy are $M_s = 6 ^\circ C$ and $A_f = 26 ^\circ C$, respectively, at cooling and heating. Tensile tests were performed on Instron machine (a ram speed of 1.5 mm/min) at different temperatures (23 °C and 200 °C). The specimens were heated with a BOSCH GHG 660 technical hot air gun; the temperature was controlled using a UT321 contact thermometer with a thermocouple attached to the center of the sample. The pulse current and ultrasonic oscillations in various sequences were introduced into the specimens at different stages of deformation and the amplitude of a stress jump from the EPE or APE effects was recorded. Regimes were as follows: frequency of 0.8 - 1 kHz, current density $j = 150$ A/mm$^2$ and pulse duration $\tau = 1 \times 10^{-4}$ s for pulse current; the frequency of 20 kHz, the duration of 1 s and the amplitude of 5 and 20 μm for ultrasound.

3. Experimental results

3.1. Tensile tests at ambient temperature

The Ti49.3Ni50.7 alloy without external impacts is characterized by high ductility ($\delta > 30$ %) and strength (800 MPa) (Figure 1, curve 1). The plateau corresponding to the martensitic transformation is short, practically passing to the inflection point. Single current pulses lead to a decrease in plasticity and multidirectional stress jumps: downward ($\Delta \sigma \sim 30-40$ MPa) and upward ($\Delta \sigma \sim 50-60$ MPa) (Figure 1, curve 2). A change in the direction of the jumps approximately corresponds to a strain of 10 %, and the stress peaks oscillate around curve 1. The use of ultrasound (Figure 1, curve 3) or a combination of pulse current and ultrasound (Figure 1, curve 4) leads to sharp embrittlement and destruction in almost elastic area. All jumps caused by ultrasound are directed downwards and have a smaller stress amplitude ($\Delta \sigma \sim 5-15$ MPa) than jumps from pulse current ($\Delta \sigma \sim 35-45$ MPa). The combined effect of ultrasound and current is similar in character to curve 3, (Figure 1, curves 3 and 4).

3.2. Tensile tests at 200 °C

Under similar tests at the temperature of 200 °C, the type of curves and the direction of the stress jumps varies. First of all, this can be seen in the absence of a plateau associated with martensitic transformation, as well as in the same direction of stress jumps “down” from the pulse current and ultrasound (Figure 2). One can note, that all the curves from pulse current and ultrasound lie above curve 1 or practically coincide with it.
The Ti$_{49.3}$Ni$_{50.7}$ alloy at 200 °C, as compared with ambient temperature, exhibits less ductility (δ ~17 %) with almost the same level of strength (850 MPa) (Figure 2, curve 1). The impact of current pulses leads to stress jumps downward with an amplitude of Δσ ~ 35-40 MPa, (Figure 2, curve 2). In the case of the ultrasound introduction, material destruction occurs already in the elastic region at stresses below 300 MPa (Figure 2, curve 3). The combined effect of current and ultrasound (Figure 2, curve 4) plasticizes the alloy, the elongation to failure of which increases from 2.5 % to 7.5 % compared with ambient temperature. The amplitude of the stress jumps from the current (Δσ ~ 35-45 MPa) is higher than the amplitude of the jumps from the ultrasound (Δσ ~ 10 MPa).

Figure 1. Stress-strain curves at ambient temperature: 1 - without external impacts, 2 - with pulse current (PC), 3 - with ultrasound (US), 4 – pulse current + ultrasound. (a) General view, (b) enlarged area for the curves 2, 3 and 4. Arrows indicate stress jumps from pulse current and ultrasound.

Figure 2. Stress-strain curves at a temperature of 200 °C: 1 - without external impacts, 2 - with pulse current (PC), 3 - with ultrasound (US), 4 – pulse current + ultrasound. (a) General view, (b) enlarged area for the curves 2 and 4. Arrows indicate stress jumps from pulse current and ultrasound.
4. Discussion

The tensile curves of the alloy at ambient and 200 °C temperatures without external impacts are presented on Figure 3, curve 1 and curve 2. For the Ti80.3Ni50.7 alloy in the austenitic phase at ambient temperature, a not typically short plateau is observed, due to the phase transformation $A \rightarrow M$, which is probably due to the proximity of the deformation temperature and $A_s$ (26 °C). The difference in elastic modulus before and after the plateau is explained by the existence, respectively, of austenite and martensite, for which the ratio $E_A > E_M$ is true [14]. The difference in the slope of the curves in the elastic deformation region is can be also explained by this fact.

The character of the tensile curve at 200 °C, which according to many literature data is higher than the deformation martensite formation temperature $M_d$, corresponds to stable austenite, which is not capable of experiencing martensitic transformation. This causes the absence of a plateau from martensitic transformation.

Now compare the deformation behaviour of the alloy with the introduction of pulse current and / or ultrasound. The introduction of single current pulses at ambient temperature leads to emergence of differently directed stress jumps caused by different physical nature. EPE causes jumps "down" at the stage of martensitic transformation, and reverse phase transformation $M \rightarrow A$ leads to stress jumps "up" at the stage of work hardening [11]. The introduction of ultrasound causes the emergence of stress jumps "down" associated with the APE, the value of which, in this case, is noticeably less than the EPE. Note that, despite the general thermal nature of the ultrasound and pulse current, they have features of the deformation effect: these are the elastic deformation of the lattice (APE), and the plastic deformation due to dislocations (EPE). Therefore, hardening due to martensitic transformation prevails under pulse current (EPE), and a relaxation effect prevails under ultrasonic action (APE), which causes softening (Figure 1, curves 2 and 3).

At 200 °C, the stress peaks have the same direction downward regardless of the deformation region. The direction of the jumps "down" indicates the absence of martensitic transformation, which is associated with the existence of stable austenite at the deformation temperature $T_d > M_d$. At the same time, EPE and APE are still present.

The combined effect of both, ultrasound and pulse current, did not reveal any noticeable differences in the deformation behaviour of the alloy, except for the increased brittleness ($\delta < 5\%$) due to low-cycle fatigue during introduction of ultrasound. However, the combined effect from APE and
EPE requires additional research with a relatively equal level of input energy or other types of metal forming.

5. Conclusions
An increase in the deformation temperature from ambient temperature to 200 °C in the Ti49.3Ni50.7 alloy leads to an increase in the flow stress. The plateau disappears due to stabilization of austenite, as well as decrease in ductility.

The direction of the stress jumps from the introduction of ultrasound (APE) and / or pulse current (EPE) is determined by the phase state of the material and the strain degree. At 200 °C, stress jumps have the same direction (downward), regardless of the strain degree. At ambient temperature, prior to the onset of strain hardening, stress jumps also have the same direction (downward), and then they become multidirectional (“down” from APE and “up” from EPE).

The different direction of the stress peaks in the shape memory alloy is related to the position of the deformation temperature regarding to the deformation martensite formation temperature. At the deformation temperature $T_d < M_a$, the direction of the jumps upwards is due to the reverse martensitic transformation caused by the thermal effect of the current. On the contrary, if the deformation temperature $T_d > M_a$, the direction of the jumps “down” corresponds to the absence of martensitic transformation.

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