Deformation and current interaction in nanostructured and amorphous Ti based alloys

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Abstract. The deformation behavior under tension and pulse current in course-grained, nanostructured and amorphous titanium based alloys is investigated. The influence of grain size, structure state and current mode on shape memory effect and electroplastic effect has been shown. Structure refinement up to nanosize area, occurrence of interphase boundaries, and amorphous state in alloys suppress the electroplastic effect. In TiNi alloys with phase thermoelastic transformation induced by deformation or temperature, current pulses decreases stress jumps downwards induced by manifestation of the electroplastic effect and increases stress jumps upwards connected with the shape memory effect.

1. Introduction

The combined application of plastic deformation and an electric current of high density ($10^3 \, \text{A/mm}^2$) results in the reduction of the applied stresses, called the electroplastic effect (EPE) [1]. It is manifested in stress jumps on the stress-strain tension curve when a single current pulse is introduced to a sample without an essential thermal effect and sample dilatation. The growth of current density and single pulse duration enhances the EPE [2]. When a multipulse current is applied, the temperature of the sample under tension increases thus much that EPE is accompanied by a thermal effect. It is assumed that the primary mechanism of EPE is the electron–dislocation interaction resulting in stress relaxation in the areas of dislocation pile-up in the crystal [3]. However, there are many other possible mechanisms described, for example, for Al or Ti-based alloys [4, 5]. Despite the large number of proposed models and mechanisms of EPE, the direct effect of electropulsing has not been well investigated. A detailed analysis of problems arising in modeling of EPE mechanisms is made in a recent review [6]. Note that such structure elements as grain size, phase morphology during the first experimental or theoretical considerations of EPE were not fully taken into consideration. For instance, the phenomenology of EPE was sufficiently fully investigated only in mono- and coarse-grained (CG) single-phase alloys [2]. It was demonstrated that EPE existed during plastic deformation of a material, and its value in relation to the flow stress varies from a few percent for polycrystals up to ten percent for monocristals [1]. However, EPE is poorly studied in...
modern materials, for example, multiphase materials, shape memory effect (SME) alloys, and ultrafine-grained (UFG) and nanostructured (NS) alloys, [7] and for amorphous alloys this information is not available at all. The study of the influence of structural features on EPE is of particular importance. The article makes an attempt to fill in the missing information. The stress-strain curves at tension under the action of a pulse current in alloys with a coarse grain, nanograin and an amorphous structure, as well as in an alloy with phase transformation (MT), are presented.

2. Materials and processing

Three kinds of materials were studied. They are commercially pure titanium (CP Ti), Grade 2 (VT1-0), two-phase Ti-6Al-4V (VT6), austenitic SME Ti$_{49.3}$Ni$_{50.7}$ alloy with CG (up to 50 μm), UFG (less than 1 μm), and NS (less than 100 nm) structures. Fig. 1 shows TEM images of materials in NS states.

![Figure 1. Microstructure of the alloys after: a - ECAE, CP Ti; b - MF, VT6; c - EPR, Ti$_{49.3}$Ni$_{50.7}$.](image)

The samples were in the form of sheets. Coarse grain structure in the alloys was processed by heat treatment. Structure refinement was achieved by severe plastic deformation, including equal channel angular extrusion (ECAE) for titanium [8], multiple forging (MF) for VT6 [9] and multi-pass cold rolling with electrical current (EPR) [10], accordingly. The processing parameters for EPR included: a strain rate of 4 m/min, a current pulse frequency of $10^3$ Hz, a pulse duration $\tau = 0.8 \times 10^{-4}$ s, a current density $j = 100$ A/mm$^2$. The temperature on the sample-simulator subjected to electropulse current of the maximal density did not exceed 150 °C. The true strain $\varepsilon = \ln \frac{h_0}{h_f}$ ($h_0$, $h_f$ - start and final thickness) was 1.4. Besides, ribbon-shaped amorphous alloys (Ti$_{50}$Ni$_{25}$Cu$_{25}$) processed by the melt-spinning technique were also investigated. Samples of alloys were exposed to tension with a pulse current $j = 100–1500$ A/mm$^2$ and $\tau = 100–1000$ μs. Dog bone-shaped tensile samples with dimensions of 0.5 x 4 x 20 mm and a test velocity about 1 mm/min were used. The ribbon samples had a cross section of 0.04 x 3 mm and a length of 75 mm.

3. Experimental results

It is discovered that the current pulse in the CG CP Ti alloy induces a typical EPE in the form of stress jumps downwards on the stress-strain curve (figure 2 a, b). The amplitude of the stress jumps depends on the density and duration of the current pulse, as well as on the grain size of the alloy structure. For example, the amplitude of stress jumps at $j = 1500$ A/mm$^2$ increases by a factor of four to five with an increase in pulse duration from 100 up to 1000 μs in single-phase CG VT1-0 annealed at 700 °C (figure 2a). In UFG CP Ti, stress jumps are not recorded at the same current density and $\tau = 100$ μs but are only observed at a $\tau = 1000$ μs (figure 2b). It is also visible that the amplitude of stress jumps is sensitive to the structural state. It decreases with a reduction of the grain size from 100–150 MPa in the CG state (figure...
(a) to 25–50 MPa in the UFG state (figure 2b). A similar tendency of decreases in EPE with reduction of
the grain size is observed in the (α + β) VT6 alloy (figure 3a, b).

\[\text{Figure 2. Deformation behavior under current (j = 1500 A/mm}^2) \text{ in the CG (a) and UFG (b) titanium.}\]

In a two-phase VT 6 alloy, the amplitude of the stress drops down is much smaller than in pure
titanium. They are equal to 15 and 5 MPa in the CG and UFG states, respectively.

\[\text{Figure 3. Deformation behavior for CG (a) and UFG (b) VT6 alloy under current (τ=1000 μs; j=1500}\]

\[\text{A/mm}^2].\]

Of particular interest are shape memory TiNi alloys with martensitic transformation at low
temperature. Depending on the chemical composition, a reverse thermoelastic martensitic transformation
occurs at temperatures of –150 to +100 °C. It was first discovered that pulsed current can cause not only
traditional stress jumps down, but also up in the CG Ti_{49.3}Ni_{50.7} alloy (figure 4a, b). It was first discovered
that pulsed current can cause not only traditional voltage surges down, but also up. It is due to this that the
amplitude of the stress jumps up increases, and the jumps down remains unchanged.
Interesting point on a tensile curve for this alloy is an area (indicated in the figures) in which neither kind of stress jump occurs, despite the introduction of a single pulse current (figure 4 a). Up to this area (strain < 6 %), the pulse current leads to occurrence of stress jumps upwards, and after that (strain > 9%) the pulse current initiates stress jumps downwards. Similar situations are observed both at a current density of 1500 A / mm² and at 3000 A / mm².

In the nanostructured TiNi alloy, stress jumps upwards can be observed instead of stress jumps downward, which completely disappear (figure 5).

As for EPE in rapidly quenched Ti₅₀Ni₂₅Cu₂₅ alloy, stress jumps at tension are not observed under current with a density of 600 A/mm² and duration of 800 μs (figure 6a). But, they appear in the ultrafine-grained alloy (grain size about 500 nm) after crystallization annealing at 500 °C for 240 s (figure 6b).
4. Discussion

The results of the study convincingly demonstrate the dependence of EPE on the structural and phase state of the studied alloys. This is especially pronounced in the large-scale effect of grain size on EPE. In titanium-based materials, the transition from a microstructure with a grain size of 20-40 microns to a nanostructure with a grain size of 100-200 nanometers dramatically reduces the amplitude of the jump (figures 2, 3).

Another important structural factor is the presence of interphase boundaries, the role of which is to decelerate the transmission of a mechanical electron pulse to dislocations and reduce the amplitude of the voltage jump. This is clearly seen when comparing EPE in single-phase titanium and two-phase titanium alloy (α + β) VT6, in which the volume fraction of interphase boundaries can be up to 25%. Interestingly, this is confirmed for coarse-grained (figures 2a, 3a) and ultrafine-grained (figures 2b, 3b) alloys. The mobility of dislocations in the crystal lattices of the hcp and bcc differs and leads to a decrease in the electron-electron diffraction, the mechanism of which is based on electron-dislocation interaction [3]. Both experimental facts related to the size effect and interphase boundaries are in good agreement with the mean free path of dislocations and their ability to multiply in the Frank-Reed source. Both parameters sharply fall upon a structural transition to the region of nanoscale or the appearance of multiphase.

A detailed study of the stress-strain curves in the Ti_{49.3}Ni_{50.7} alloy showed that the parameters of the stress jump are determined by the combined action of two different in nature effects: EPE (downward jump) and SME (upward jump). The SME jump is due to the difference in the stresses of the flow of austenite and martensite coexisting at the initial stage of deformation even with slight heating of the alloy due to the martensitic transformation B19′→B2 [11]. As noted above, EPE is close to zero in the nanostructured state, which leads to the manifestation of only SME and the associated upward voltage jump (figure 5). The decrease in the amplitude of the stress jump in NS Ti_{49.3}Ni_{50.7}, depending on the degree of deformation is determined by the change in the ratio of the volume fraction of the martensitic and austenitic phases, as well as the stabilization of one of these phases. In fact, the thermoelastic MT A→M caused by stress arises in the stress region in which $v_m / v_a$ varies from 0 to 1 [12]. With increasing stress, the volume fraction of unstable austenite decreases, the volume fraction of stable martensite increases. As a result, the amplitude of one of the effects decreases, and the other effect increases, respectively. An interaction of EPE with SME reduces the amplitude of the step up.
In the initial rapid quenched shape memory alloy, EPE is absent (figure 6a), but it appears in the UFG state with a grain size of 500 nm, obtained by crystallization. The experiment confirms the disappearance of EPE with a decrease in size to the nano-region. Indeed, the absence of mobile deformation carriers in amorphous materials does not contribute to the manifestation of EPE. As a rule, crystallization of an alloy contributes to the occurrence of dislocations and the manifestation of EPE. The mode and type of current are also of great importance. An increase in the main current parameters contributes to an increase in the energy and amplitude of stress jumps. This is why an increase in the number of current pulses also increases the amplitude of the jump. It is known that the Joule effect from a multipulse current with duration of up to 1 ms can lead to more significant stress jumps of up to 500 MPa than in the case of the application of single pulses in SME alloy [13].

5. Conclusions
The effect of the initial structure-phase state and current regimes on the stress-strain curves was studied in a CG, UFG, NS and an amorphous VT1-0, VT6, TiNi alloys. The pulse current resulted in the appearance of stress jumps up or down on the stress–strain curves due to the manifestation of the electroplastic effect and martensitic transformation, accordingly. An amplitude and direction of the stress jumps depend on structure features (grain size, phase composition), phase transformations in alloys, and current energy.

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