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INFLUENCE OF STRUCTURE REFINEMENT ON ELECTROPLASTIC EFFECT IN SHAPE MEMORY TiNi ALLOYS

V.V. Stolyarov[1, 2]

[1]Mechanical Engineering Research Institute of Russian Academy of Sciences, Moscow, 101990, Russia,

[2]National Research Nuclear University MEPhI, Moscow, 115409, Russia

*e-mail: vlstol@mail.ru

Abstract. The influence of structure-phase features and electric current modes on the electroplastic effect (EPE) revealed at tension for coarse-grained, nanocrystalline and amorphous TiNi-based alloys is investigated. Grain-size refinement up to nanoscale and amorphization in alloys lead to decreases or even full disappearance of EPE. In nanocrystalline alloys with reverse thermoelastic martensite transformation, the introduction of current pulses suppresses downwards stress jumps induced by the EPE and causes active upwards stress jumps connected with the shape memory effect (SME).

1. Introduction

It is well-known that the joint action of plastic deformation and an electric current of the large density (10^3A/мм^2) lead to a decrease in the applied stresses, named by electroplastic effect (EPE) [1]. It is displayed in stress jumping on a stress-strain tension curve when a single current pulse is introduced to a sample without an essential thermal effect and sample dilatation. It is supposed that the primary mechanism of EPE is electron-dislocation interaction resulting in stress relaxation in areas of dislocations pile-up in a crystal [2]. The phenomenology of EPE has been sufficiently fully investigated in monocrystals and coarse-grained (CG) single-phase metals [3]. It is shown that EPE exists only during plastic deformation of a material, and its value in relation to a flow stress varies from a few percent for polycrystals up to ten percent for monocrystals [1]. However EPE is poorly studied in modern materials, for example, multiphase materials, shape memory effect (SME) alloys, and nanocrystalline (NC) alloys [4], and for amorphous alloys these data are absent in general. Research on the influence on EPE on structural factors such as the grain size and phase state represents a special interest. In this work, an attempt is made to fill this gap. The experimental data received under tension in conditions of the introduction of a pulse current in shape memory alloys with CG, NC, and amorphous structures are demonstrated.

2. Materials and processing

The investigated materials were shape memory $Ti_{50}Ni_{50}$ and $Ti_{49.3}Ni_{50.7}$ alloys with CG (up to 50 μm), and NC (less than 100 nm) structures. The samples were in the strip form with section of 2x6 mm. CG states in alloys have been received by thermal treatment (annealing or quenching). NC states were processed by deformation method - a cold rolling with a current [5]. Besides, there were also investigated amorphous $Ti_{50}Ni_{25}Cu_{25}$ alloy in ribbon form with the section of 0.040 x 1.8 mm and length of 70 mm processed by the single-roller melt-spinning technique under argon atmosphere [6]. Afterwards, the ribbons were subjected to a heat treatment at 450 °C for 10 min to promote full crystallization and formation ultrafine-grained microstructure with grain size of 0.5–1 μm [7]. Samples of alloys were exposed to tension at strain rate $10^{-3}s^{-1}$ with a pulse current of density j =100 - 1500 A/mm^2 and duration τ = 100 - 1000 μs. In order to compare EPE in the investigated materials one experiment has been performed on the metal without phase transformation in wide temperature area. For this aim the commercial pure Ti in CG and ultrafine-grained (UFG) states has been used. Both states were processed by annealing and cold rolling with current, correspondingly. Structure investigations were performed by transmission electron microscopy on JEM 100CX.

3. Experimental results

The introduction of the current pulse in CG Ti alloy with mean grain size of 15 μm induces typical EPE in the form of stress jumps downwards on the tension stress–strain curve (Figs. 1a,b).

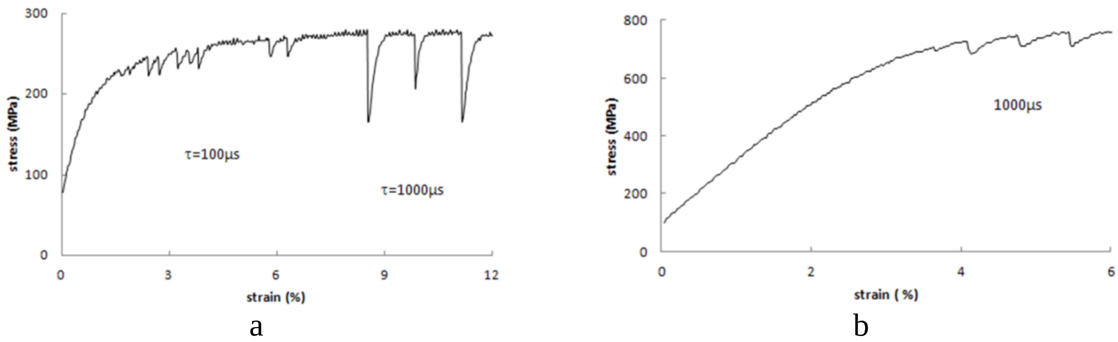


Fig. 1. Stress-strain curves with current (j = 1500 A/mm^2) in CG (a) and UFG (b) Ti [4, 8].

The amplitude of stress jumps depends on the density and duration of the current pulse and also on the grain size of the alloy structure. For example, the amplitude of stress jumps at a current density of 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 Ti annealed at 700 °C (Fig. 1a). In UFG Ti with mean grain size of 500 nm, stress jumps are not registered at the same current density and pulse duration of 100 μs but are only observed at pulse duration of 1000 μs (Fig. 1b). 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 CG state (Fig. 1a) to 25–50 MPa in UFG state (Fig. 1b).

EPE in alloys with the martensitic transformation at low temperatures is of special interest. An example of such materials is shape memory TiNi alloy in which, depending on the chemical composition, a reverse thermoelastic austenite-martensite transformation occurs at temperatures of –150 to +100 °C. For the first time it was revealed that the pulse current in CG $Ti_{49.3}Ni_{50.7}$ alloy with mean grain size of 80 μm leads to the occurrence of stress jumps not only downwards but also upwards (Fig. 2).

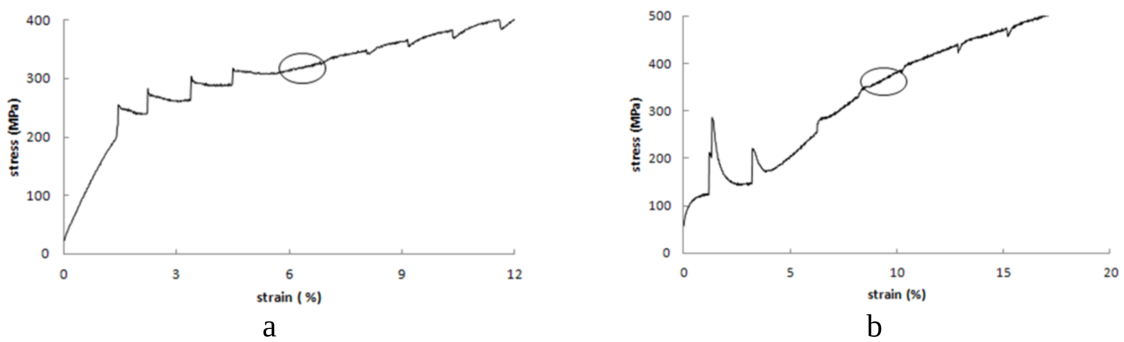
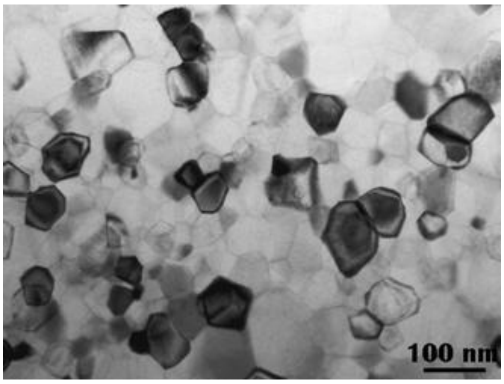
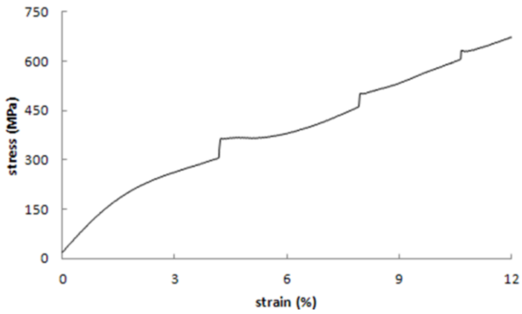


Fig. 2. Stress-strain curves in CG $Ti_{49.3}Ni_{50.7}$ alloy with current:
a – j=1500 A/mm^2; b – j=3000 A/mm^2 [4].

Therefore, the amplitude of stress jumps upwards rises with increases in the current density but remains constant for stress jumps downwards. Another feature of this alloy is the presence of the area (designated in figures) on a tension curve in which neither kind of stress jump occurs, despite the introduction of the single pulse current in this place.



a

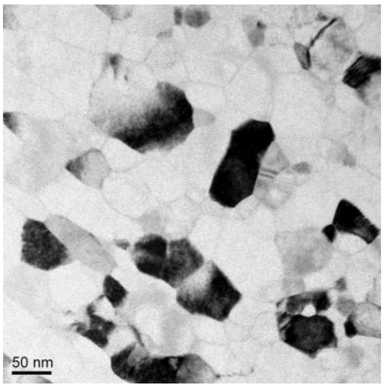


b

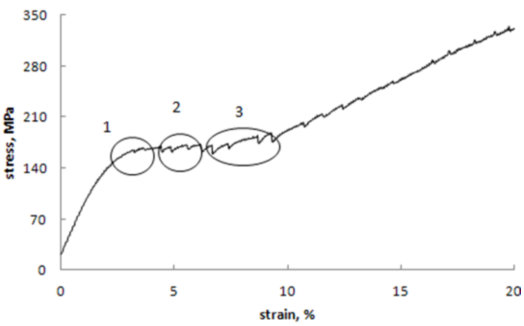
Fig. 3. Microstructure (a) and stress-strain curve with current density of 1500 A/mm^2, (b) in NC $Ti_{49.3}Ni_{50.7}$.

In the NC $Ti_{49.3}Ni_{50.7}$ alloy with grain size less than 100 nm (Fig. 3a), upwards stress jumps occur with decreasing amplitude with strain instead of stress jumps downward, which completely disappear (Fig. 3b).

Deformation behavior of the stoichiometric $Ti_{50}Ni_{50}$ alloy differs from the alloy mentioned above. Microstructure of $Ti_{50}Ni_{50}$ alloy in NC state with mean grain size of 50 nm processed by electroplastic rolling and the following annealing is presented in Fig. 4a. Stress-strain curves with current for the alloy in CG and NC states are shown in Figs. 4 b,c.



a



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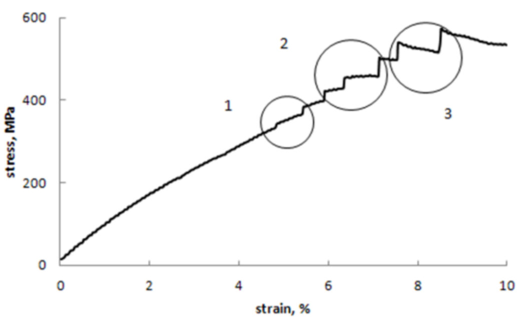
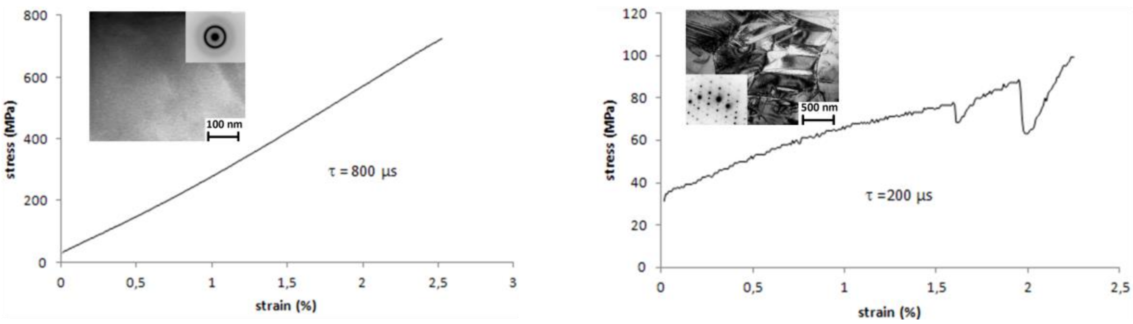


c

Fig. 4. Microstructure (a) and stress-strain curves with current (b, c) in $Ti_{50}Ni_{50}$:
b – CG state; c – NC state; 1- j = 500A/mm^2, 2 - j = 1000A/mm^2, 3 - j = 1500A/mm^2.

Unlike the over stoichiometric $Ti_{49.3}Ni_{50.7}$ alloy (Fig. 3b) stress jumps in the stoichiometric $Ti_{50}Ni_{50}$ alloy on a horizontal plateau are downward ones (Fig.4b). The amplitude of jumps down gradually decreases with a strain, and then the direction of jumps changes on the opposite one. The deformation behavior with current of $Ti_{50}Ni_{50}$ alloy in NC state is similar to $Ti_{49.3}Ni_{50.7}$ alloy in NC state (Fig.3b). All arising stress jumps have the direction up (Fig.4c). For both states increase of current density from 500 to 1500 A/mm^2 causes increase in the amplitude of stress jumps.

Let us consider EPE in melt-spun alloys with initially amorphous structure. In $Ti_{50}Ni_{25}Cu_{25}$ with amorphous structure, EPE on a stress–strain curve is not observed during the introduction of single current pulses with density of 600 A/mm^2 and duration of 800 μs (Fig. 5a). However, there are significant stress downwards jumps in a state after crystallization annealing (Fig. 5b).



a b

Fig. 5. Microstructures (inserted) and stress-strain curves with current density of 600 A/mm^2 in melt-spun $Ti_{50}Ni_{25}Cu_{25}$: a – before annealing; b – after crystallization annealing.

4. Discussion

The presented results clearly show the sensitivity of EPE to the structure state and phase composition of the investigated materials. First of all, this is related to the influence of the grain size on the EPE. In the single-phase Ti refinement of the grain size from several tens of microns up to several hundred nanometers leads to multiple reductions of the stress jump amplitude; that is, EPE is suppressed (Figs. 1). The experimental results are in good agreement with the EPE mechanism that is realized due to electron–dislocation interaction [2]. The observable dependence of EPE on structure refinement can be explained by the intragrain dislocations' mobility and ability to nucleate. It is well-known that dislocation mobility and nucleation fall sharply with decreases in grains up to nanosize and the presence of interphase boundaries.

The research on EPE in $Ti_{49.3}Ni_{50.7}$ alloy with thermoelastic reverse transformation has shown that the direction of the stress jump upon the introduction of a current pulse can be not only downwards but also upwards (Fig. 2a). Moreover, structural refinement leads to the disappearance of stress jumps downwards and to the occurrence of stress jumps upwards only (Fig. 2b). The careful analysis of the nature of stress jumps in $Ti_{49.3}Ni_{50.7}$ allowed establishing that the direction and amplitude of the stress jump is defined by the superposition of EPE (jump downwards) and SME (upwards). The latter is caused by an increase of the yield stress of B2-phase during the reverse martensitic transformation B19'→B2 due to the current heating effect [9].

As in nanocrystalline state EPE is appreciable less than SME or even close to zero the result is stress jump upwards (Fig. 3b). Reduction of stress jump amplitude in NC $Ti_{49.3}Ni_{50.7}$ with strain degree is specified by change the ratio of austenitic and martensitic phases, and also by stabilization of one of these phases. Because EPE is appreciably less than SME or even close to zero in a nanostructured state, the result is a stress jump upwards.

Change of chemical and, respectively, phase composition in CG TiNi alloys leads to change in sequence of stress jumps up and down. In the initially martensitic $Ti_{50}Ni_{50}$ alloy the appearing jumps down with deformation are transformed to jumps up (Fig. 4b), and in the initially austenitic alloy $Ti_{49.3}Ni_{50.7}$ this sequence changes on the contrary (Fig. 2a). Temperature dependence of flow stresses and a quantitative ratio of austenitic (A) and martensitic (M) phases in an initial alloy are the main reasons for such different deformation behavior under the influence of single impulses. In fact, a quantitative ratio is expressed as A>> M and M>> A in $Ti_{49.3}Ni_{50.7}$ and $Ti_{50}Ni_{50}$, respectively. Regarding flow stress it increases with temperature for M-phase and decreases for A-phase [10]. Nevertheless, this assumption needs additional structural research in future. It was shown above that EPE is suppressed in NC state, that is why the type of stress-strain curves and character of stress jumps for both alloys is identical (Fig. 3b and Fig. 4c).

In melt-spun amorphous $Ti_{50}Ni_{25}Cu_{25}$ alloy, EPE is absent (Fig. 5a), but it appears in the crystal state processed by annealing (Fig. 5b). This fact is in agreement with the reduction and disappearance of EPE in nanocrystalline structures. Really, it is not observed because of the absence of free dislocations in range-ordering areas in amorphous materials. On the contrary, crystallization of alloys promotes the occurrence of dislocations and the display of EPE.

The modes and kind of current also have an influence on the EPE. As the current density and pulse duration increase, the pulse energy of these parameters raises the amplitude of stress jumps. For the same reason, the change from single pulses to a multipulse current leads to the same effect.

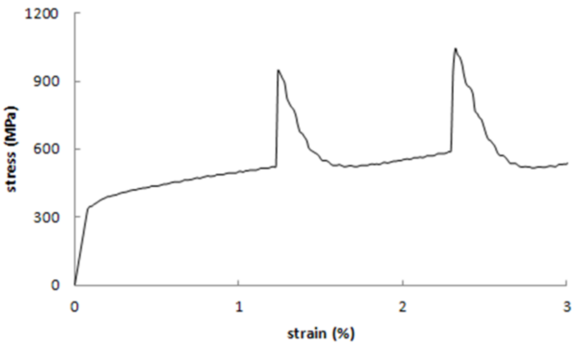


Fig. 6. Stress-strain curve with multipulse current in NC $Ti_{49.3}Ni_{50.7}$ alloy [11].

For example, earlier it was shown for $Ti_{49.3}Ni_{50.7}$ alloy that the Joule effect in the case of application of a multipulse current with duration up to 1 ms can lead to more significant stress jumps up to 500 MPa (Fig. 6) than in the case of the application of single pulses [11].

5. Conclusions

The influence of an initial structure-phase state and the current mode on deformation behavior under tension in shape memory TiNi alloys was investigated. The pulse current leads to the occurrence on the stress–strain curves of stress jumps conditioned by the electroplastic effect and the austenite-to-martensite transformation. It was shown that the amplitude and direction of stress jumps depend on structure refinement, ratio of austenite / martensite phases in the initial or deformed alloy, and modes of pulse current.

Acknowledgements

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