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ELECTROPLASTIC EFFECT IN NANOSTRUCTURED TITANIUM ALLOYS

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Abstract. Features of the influence of plastic deformation in the presence of electrical current on the structure and mechanical properties of titanium alloys VT1-0, VT6, and $Ti_{49.3}Ni_{50.7}$ in coarse-grained (CG) and ultrafine-grained (UFG) states were investigated. Introduction of a pulse current during cold rolling leads to the increase in deformability, and during tension loading it causes occurrence of stress jumps connected with phase transformation or electroplastic effect (EPE). It is shown that EPE is the structurally-sensitive property dependent on the grain size.

1. INTRODUCTION

Bulk ultrafine-grained (UFG) materials are currently a major focus in materials science due to their unique properties by comparison with their coarse-grained counterparts [1]. Porosity- and contamination-free bulk UFG metals and alloys can be produced by severe plastic deformation (SPD) [1]. Recently, novel SPD methods were elaborated where the efficiency of plastic deformation in grain refinement was increased by a simultaneous application of pulsed electric current [2,3]. These procedures are called as electroplastic deformation methods. The major effect of the current pulses was to reduce the flow stress [4,5]. The plasticity of materials had been significantly improved concurrently [6]. The method of severe plastic deformation like ectroplastic rolling (EPR), can allow creating nano- or UFG structures. This approach is based on the application of EPR and nanostructuring by cold rolling with a current [3]. The present article is devoted to the investigation of EPE influence on the structure and properties of titanium alloys VT1-0, Grade-4, VT6 and TiNi in coarse-grained (CG) and UFG states.

2. EXPERIMENTAL PROCEDURE

The coarse-grained (CG) state with the grain size of 20 to 50 microns in materials has been produced by the annealing at 700 °C (VT1-0 and Grade-4 alloys), annealing in the two-phase area of a phase diagram at 900 °C (VT 6 alloy) and quenching from 800 °C in water ($Ti_{49.3}Ni_{50.7}$ alloy). UFG structure is processed by EPR technique (VT6 and $Ti_{49.3}Ni_{50.7}$) and equal-channel angular pressing (ECAP) (VT1-0 and Grade-4). Multipass EPR has been executed on strips of section 2x6 mm^2 with simultaneous introduction an unipolar pulse current with density j=80-100 A/mm^2, pulse duration (1-10) x10^{-4} s^{-1} and frequency of 10^3 Hz; further details are described in Ref. [1]. Deformability of strips estimated by true strain $e = \ln t_i / t_f$, where t_i, t_f - an initial and final strip thickness.

Structure examinations and mechanical tests have been performed on the samples after annealing at 450 and 600 °C where there are appreciable structural changes like stress relaxation, recrystallization or ageing. The microstructure was investigated on thin foils by the transmission electron mi-

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croscopy (TEM) JEM-2100. The foils were prepared by spark cutting, mechanical thinning and electropolishing of sample in the cross-section. Phase and texture analyses were performed with Rigaku diffractometer in $Cu_{k\alpha}$- radiation.

The mechanical behaviour was studied by tension at speed of 0.5 mm/min by MTS Systems, model 43, USA (without a current) and horizontal set IM-5081 (with a single and multipulse current).

3. EXPERIMENTAL RESULTS

3.1. Deformability

Table 1 shows that deformability of titanium alloys for rolling with current is 1.15 - 5.4 times higher than that without current. It is visible that the effect of EPR with current depends on chemical and phase composition of alloys, and also on the grain size in their structure. The smallest effect was observed in the coarse-grained pure titanium VT1-0 and Grade-4 and the greatest in the two-phase alloy VT6. There is a tendency to increasing of this effect in UFG state in comparison with CG state in single-phase alloys, and also in alloy VT6 at transition from two-phase to a single-phase state.

Character of deformation hardening during EPR at identical current density differs for alloys of the various natures (Fig. 1). For example, in the pure titanium it is observed as weak hardening (curve 1), and weak softening (curve 2), connected with the different grain size in initial structure. In the intermetallic alloy TiNi the hardening degree is the greatest (curve 3).

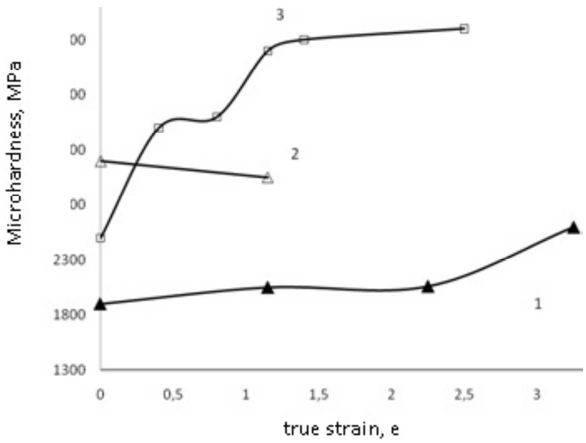

Fig. 1.Microhardness dependence on true strain at EPR: 1 – CG VT1-0; 2 – UFG VT1-0; 3 – CG TiNi.

3.2. Microstructure

TEM data of EPR alloys after post-deformation annealing have shown presence of nanocrystalline B2

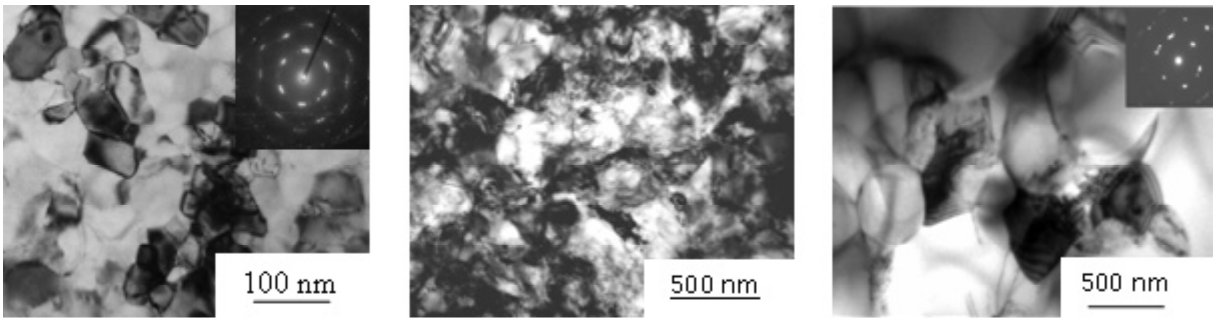

Fig. 2. Microstructure of alloys after EPR and annealing: a - $Ti_{49.4}Ni_{50.6}$, 450 °C-1 h, *e* =1.81 ; b - VT1-0, 450 °C-1 h, *e* = 1.2; c – VT6, 600 °C-1 h, *e* = 1.8.

Table 1. True strain to failure at cold rolling with a current and without a current.

Alloy	Structure state	$e_{j=0}$ without current	e_j with current	e_j / $e_{j=0}$
Ti (Grade 4)	CG	2.0	2.3	1.15
	UFG	2.0	2.3	1.15
Ti (VT1-0)	CG	2.3	3.2	1.4
	UFG	0.5	1.2	2.5
$Ti_{49.3}Ni_{50.7}$	CG	0.8	2.5	3.1
	UFG	0.5	1.9	3.8
VT6 ($\alpha + \beta$)	CG	0.55	2.4	4.3
(β)	CG	0.35	1.9	5.4

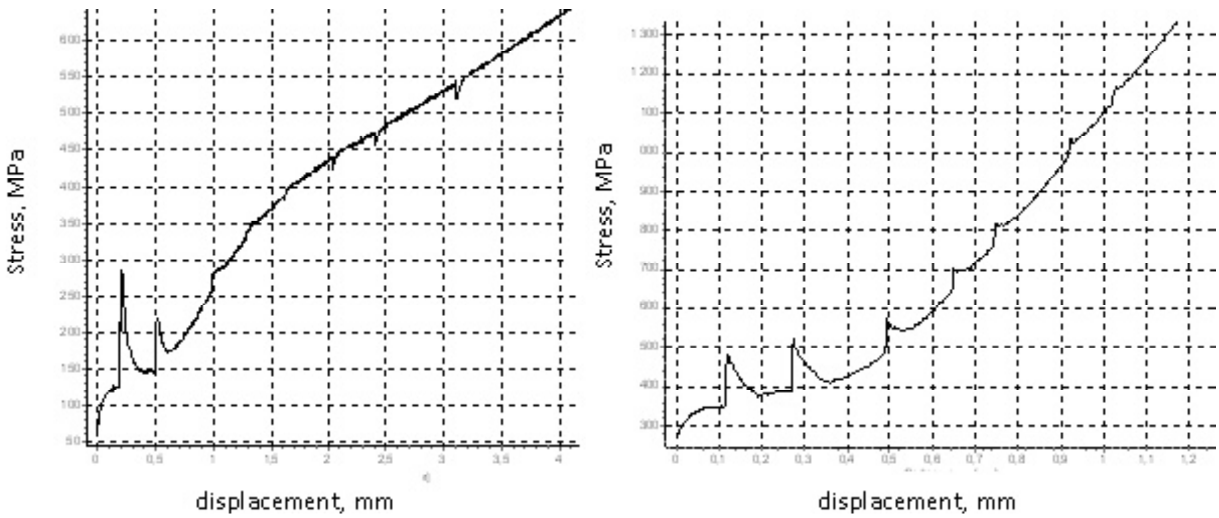

Fig. 3. Stress-strain curves with single current pulses for TiNi alloy in CG (a) and NS (b) states.

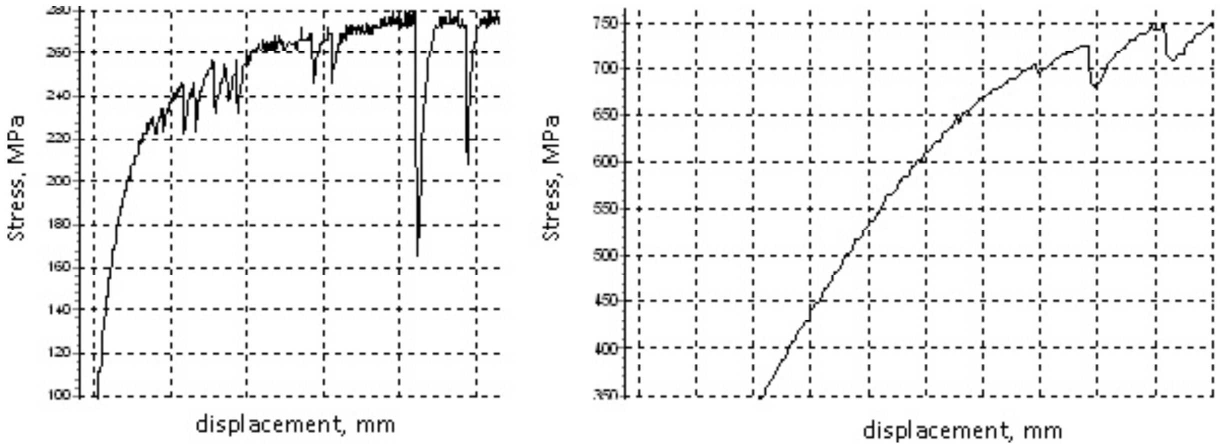

Fig. 4. Stress-stress curves with pulse current in CG (a) and UFG (b) titanium.

(Fig. 2a) or sub-microcrystalline (Figs .2b and 2c) structures. The analysis of diffraction patterns of the deformed TiNi alloy before annealing has confirmed presence of martensitic B19' phase in small amounts and crystallographic texture type (200).

Severe EPR could result not only to structure refinement, but also to possible changing of initial phase composition in multi-phase alloys and to affect on view of stress-strain curves. Therefore, X-ray analyses of two-phase VT6 alloy was performed. The X-ray data testified that after EPR of VT6 alloy the quantity of β - phase decreases from 10-15% to 1-2% due to deformation dissolution in matrix α-phase. However, the new phases have not been observed.

3.3. Mechanical behavior

Mechanical behaviour of alloys after EPR and post-deformation annealing is presented by the properties at tension tests (Table. 2) and stress-strain curves (Figs. 3 and 4). Alloys in nanostructured state (NS) produced by the EPR and subsequent annealing have better strength properties than those in the CG state. This is demonstrated by the tension test with and without applied electrical current.

Distinctive feature of stress-strain curves with applied pulse current is the occurrence of stress jumps, each of which corresponds to a single current pulse. A direction (up, down) and amplitude of stress jump are different. They depend on the chemical composition of an alloy and its structural state. In the presence of phase transformation (TiNi) both kinds of stress jumps are observed at tension (Fig. 3à). Without phase transformations there are only jumps downwards (Fig. 4). The detailed analysis of the physical reason of jumps testifies to the phase transformation (jumps upwards) or to the EPE action (jumps downwards) [2,3]. The amplitude of stress jumps for CG Ti is two times higher than that for UFG Ti. It shows that the EPE decreases with decreasing grain size. Similar influence of grain size on EPE is observed also in the TiNi alloy. EPE is present in CG state and is absent in NS state

Table 2. Mechanical properties of the Ti-based alloys at tension with a current and without a current.

Material	Treatment	State	UTS, MPa	YS, MPa	$\Delta\sigma$, MPa
VT1-0	annealing	CG	300/350	180/190	100
	EPR+ 450 °C	UFG	750/800	550/550	50
$Ti_{49.4}Ni_{50.6}$	Quenching	CG	750/940	400/600	25
	EPR + 450 °C	NS	1300/1300	1170/1200	0
VT6	annealing	CG	-/900	-/820	25
	EPR +600 °C	UFG	-/1015	-/950	5

In numerator and denominator are properties at tension with a current and without a current.
$\Delta\sigma$ - average amplitude of stress jump at a single current pulse.

(Fig. 3a, b). The possible reason of the EPE absence in NS alloy is insufficiently high current density for the given alloy. Additional investigations of EPE depending on current density are required.

4. CONCLUSIONS

Electroplastic rolling forms ultrafine-grains, and the nanostructured state, raises deformability and strength of alloys VT1-0, Grade-4, VT6 and $Ti_{49.3}Ni_{50.7}$. Electroplastic effect is the structurally-sensitive property whose magnitude decreases due to structure refinement and even disappears in nanocrystalline state

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