DOI: https://doi.org/10.26896/1028-6861-2023-89-8-62-66

THE ELECTROPLASTIC EFFECT IN COARSE-GRAINED AND ULTRAFINE-GRAINED TITANIUM

© **Vladimir V. Stolyarov**

Mechanical Engineering Research Institute of RAS, 4, Maly Kharitonievsky per., Moscow, 101990, Russia; e-mail: vlstol@mail.ru

Received January 17, 2023. Revised February 22, 2023. Accepted March 30, 2023.

One of the well-known features of the external action of the electric current in the process of plastic deformation is the electroplastic effect manifesting in a decrease in flow stresses and an increase in plasticity (deformability). Understanding the nature of the electroplastic effect provides targeted regulation and application of the effect to improve the efficiency of metal working processes or to change the structure and properties of materials. The deformation behavior of commercially pure titanium under the impact of an electric current of critical density from 12 to 400 A/mm^2 is considered. The electroplastic effect in coarse-grained (d = 50 μm) and ultrafine-grained (d = 500 nm) VT1-0 titanium has been studied under a combination of tensile deformation and applied current of various modes and regimes, including the single-pulse, multipulse and direct current modes. It is shown that a decrease in the grain size contributes not only to an increase in the strength characteristics, but also to a decrease in the electroplastic effect, the mechanism of which is closely related to the density of mobile dislocations. It has been shown that the manifestation of the electroplastic effect in titanium is controlled by the grain size, and a decrease in the grain size leads to its electroplastic degradation and finally to the complete disappearance in the amorphous state due to a decrease in the density of free dislocations.

Keywords: titanium; grain size; tension; stress; strain; electroplastic effect; current; single pulses; multipulse current; direct current.

Introduction

The electroplastic effect (EPE) that has been discovered more than fifty years ago manifests itself in a significant decrease in the flow stress of metallic materials during deformation in the presence of a high-density current [1, 2]. Therefore, the attention of researchers was initially drawn to a practical application of EPE, which has happened to be quite wide and can be found in published studies [3, 4]. They are mainly focused on metal forming (stamping, rolling, drawing, pressing), solid state welding and cutting brittle and hard deformed materials to reduce roughness. Moreover, the possibility of microstructure refinement in elongated materials has demonstrated a control of the functional properties of materials [5]. The limitation in the widespread use of EPE is associated with high critical current density required for a noticeable effect on deformability: for many industrial materials it should be $j_{cr} > 10^2$ A/mm^2 [2]. That is why the effective cross-section of various semi-finished products such as wire, rods and sheets do not exceed 1 – 10 mm^2, which is associated with the requirement to create high-power current generators.

Another area of research has been the physical nature of EPE. In [6], calculations have shown that the thermal effect, determined by the electrical and thermal conductivity of the sample, is the only cause of EPE. However, even in the first studies, it became clear that the usual thermal effect cannot fully explain the EPE, since the drop in stresses was noticeably larger than it could be due to the temperature dependence of the flow stresses. In the review [7], it was shown that the main contribution to the EPE is made by the electronic “wind,” which causes the mobility of dislocations and the thermal effect of the current. Other accompanying EPE electromagnetic (skin, pinch) and magnetostrictive effects are an order of magnitude smaller.

Recent articles trying to explain EPE by associating it with breathers [8] or with nonequilibrium processes in the electronic and phonon sub-systems when an electric current of high density flows through metal [9]. These processes lead to a deviation of the average energy of dislocation oscillations from that, which corresponds to the lattice temperature. As a result, the frequency of fluctuation overcomes obstacles by increase in dislocations [10]. A more general point of view is that all mechanisms can act simultaneously, the relative contribution of which varies depending on material,

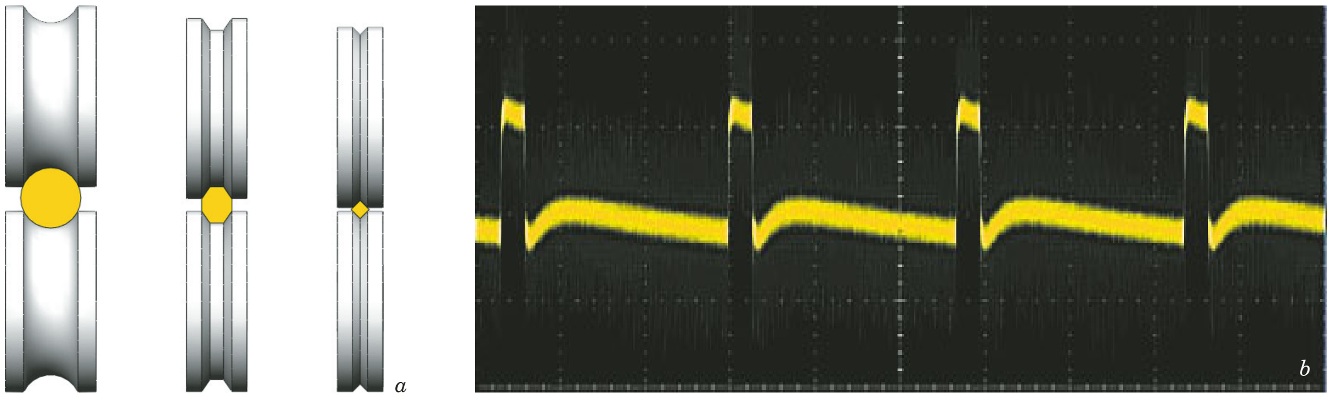

Fig. 1. Scheme of the rolling in calibers (*a*) and oscillogram of pulse current (*b*)

external conditions, size and shape of samples, etc. [11].

As for the materials under study, originally they used to be single crystals of pure metals, and then have changed to polycrystals (Zn, Cd, Sn, Pb, In, Ni, Fe, Nb, Ti, Al, Cu, W) and industrial structural alloys based on aluminum, copper and steel. Recently, nano- and amorphous materials [12], TRIP steel [13], functional materials with shape memory, have been also investigated, where the direction of stress reduction was found to be not only downwards, as found previously, but also upwards [14]. Titanium [2, 15 – 17, 19] and titanium-based alloys [5, 12, 14, 18] occupy a prominent place among the materials under study, as the main materials for aerospace sector and medical implants, especially in the nanostructured state. Note that most of the cited above studies of EPE were carried out on materials in a coarse-grained state with a grain size more than 1 – 10 μm with rare exceptions [20].

Taking into account the importance of the grain size effect on the mechanical properties and deformability of titanium, the purpose of this work is to compare the deformation behaviour of coarse-grained and ultrafine-grained titanium under different current modes.

Experimental materials and methods

A material for the study was technically pure titanium VT1-0, with impurity content shown in Table 1. The initial material form was a rod with a diameter of 10 mm.

The sample has been processed by multi-pass electroplastic rolling in calibers according to the scheme "circle – hexagon – rhomb" (Fig. 1*a*) and has been shaped into the wire with a cross section of 1.55×1.85 mm^2. Some details of electroplastic rolling can be found in [5]. The total deformation degree and the rolling speed were 90 % and 50 mm/sec, respectively. Rolling in calibers was carried out with the introduction of a multi-pulse current with duty factor of 10, a density of 100 A/mm^2, a pulse duration of 10^{-4} sec and a frequency of 1000 Hz (Fig. 1*b*). The wire was investigated in two structure states formed by annealing at temperatures of 700 and 500°C for 30 min, respectively.

Tensile tests were performed on the horizontal testing machine IR-5047-50 at room temperature with the speed 1 mm/min and the following current modes/regimes (density j, frequency ν, and pulse duration τ): 1 — no current; 2 — single pulses $j = 400$ A/mm^2, $\tau = 1$ msec; 3 — multi-pulse current $j = 100$ A/mm^2, $\tau = 0.1$ msec, $\nu = 1000$ Hz; 4 — direct current, $j = 12$ A/mm^2. The sample gauge length for mechanical tests was 25 mm. During tension, the sample temperature was measured with a thermocouple fixed in the middle of the sample gauge length.

Schemes of pulsed current supply to the sample during electroplastic rolling in calibers and during the tensile tests are shown in Fig. 2. In both cases, a 7 kW pulse current generator was used, which made it possible to reproduce the current of different modes (single pulses, multipulse and direct current) and regimes ($j = 500 – 5000$ A, $\tau = 30 – 1000$ μsec, frequency 1 – 1000 Hz). To prevent current leakage during the tensile test, the gripping parts were insulated with polystyrene.

Table 1. Chemical composition of titanium (wt.%)

Material	C	Fe	Si	O	N	H	Al
VT1-0	0.07	0.18	0.10	0.12	0.04	0.01	0.6

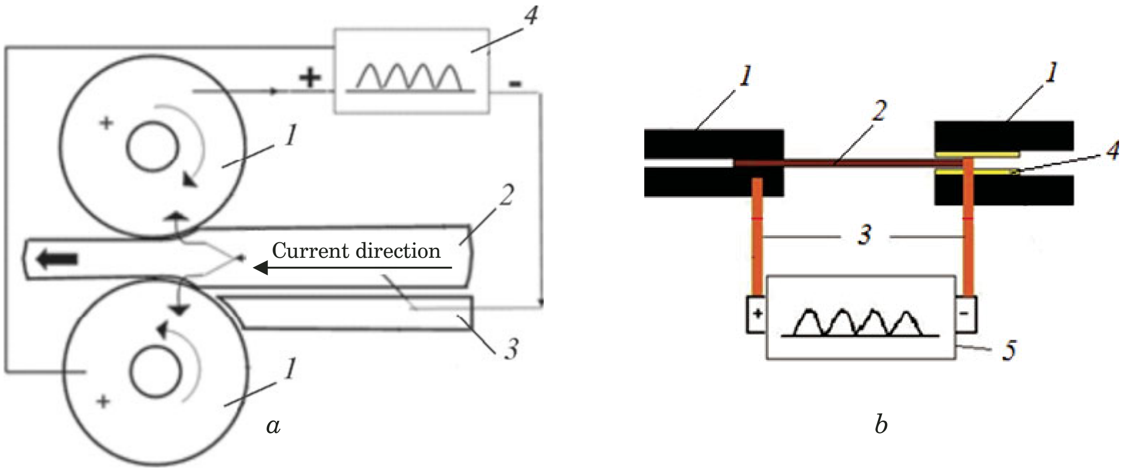

Fig. 2. Scheme of the current supply during electroplastic rolling (*a*) and tensile test (*b*): *a*, *1* — mills; *2* — wire; *3* — feed table; *4* — pulse current generator; *b*, *1* — grips; *2* — sample; *3* — bus line for supplying current; *4* — insulation; *5* — pulse current generator

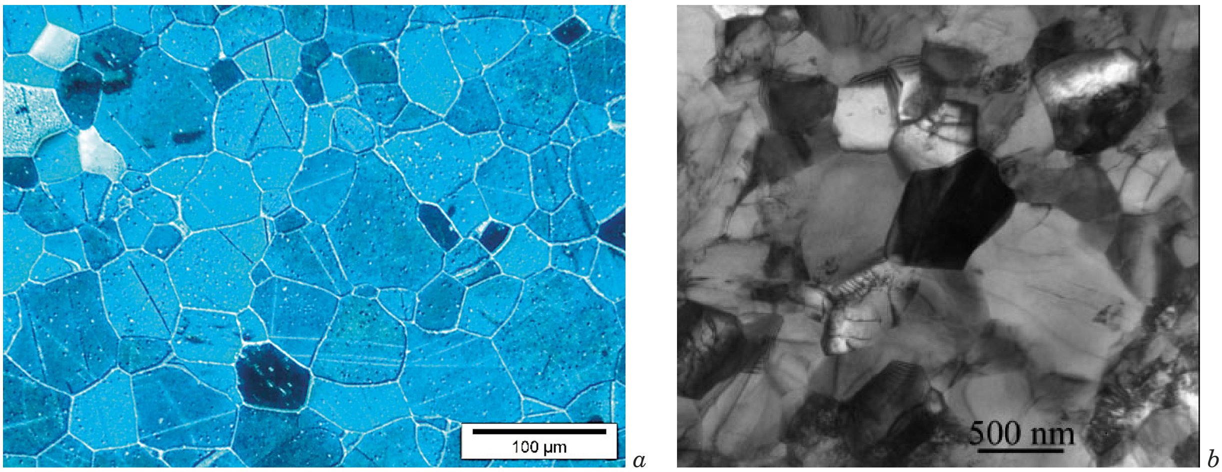

Fig. 3. Microstructure of coarse-grained titanium observed with optical microscopy (*a*) and ultrafine-grained titanium observed with TEM (*b*)

Experimental results and discussion

The microstructures of the samples annealed at 500 and 700°C are shown in Fig. 3. A large difference in grain size can be noted, which is two orders of magnitude.

Annealing at 700°C of heavily hard-worked titanium caused recrystallization, which partially has the features of collective recrystallization (Fig. 3*a*). The grain boundaries are rectilinear, and there is insignificant number of twins and particles of impurity elements inside the grains, mainly oxides and aluminides. The average grain size is 50 µm. The structure of titanium can be classified as coarse-grained one. Annealing of hard-worked titanium at 500°C led to the formation of incompletely recrystallized fragmented structure with an average sub-grain size of 500 nm and a fairly high density of dislocations inside the grains (Fig. 3*b*). The structure of titanium can be described as ultrafine-grained one.

Figure 4 shows the stress-strain curves under different tensile test conditions of titanium in the coarse-grained (Fig. 4*a*) and ultrafine-grained (Fig. 4*b*) states.

First of all, it is seen that the flow stresses for ultrafine-grained titanium for all current modes are higher than for the coarse-grained titanium. Under tension without current, a reduction in grain size by two orders of magnitude led to more than double increase in strength and more than four times decrease in ductility (Table 2), which is directly related to the well-known effect of grain size (Hall – Petch effect).

The current introduction of any mode, except for single pulses, leads to a decrease in the flow stresses and relative elongation to failure. If the decrease in plasticity is associated with strong neck formation of titanium and, accordingly, with a mul-

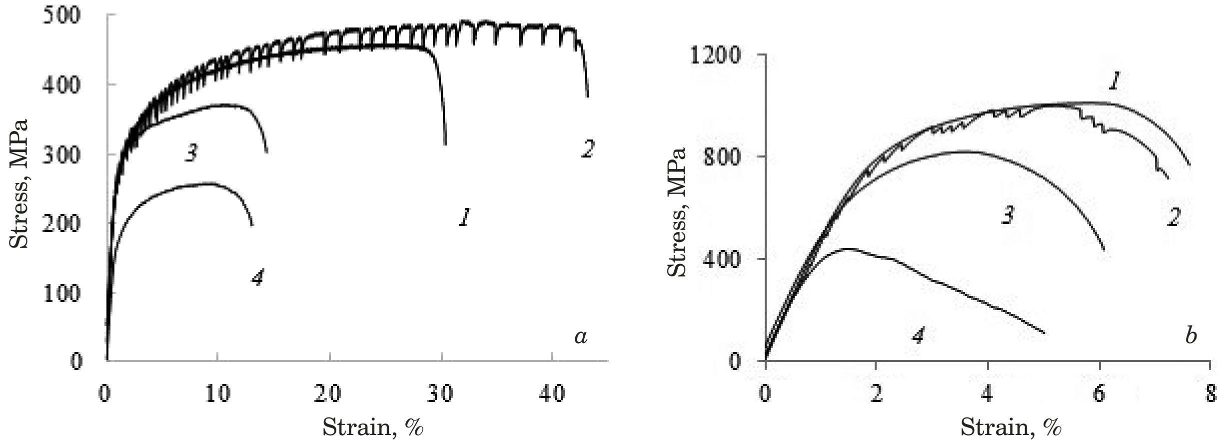

Fig. 4. Stress-strain curves of course-grained (*a*) and ultrafine-grained (*b*) titanium under different current modes: *1* — without current; *2* — single pulses; *3* — multipulses; *4* — direct current

tiple increase in the actual current density, then the decrease in the flow stress is due to the total action of thermal and electroplastic effects. In this case, the contribution of the thermal effect in comparison with the electroplastic effect should be noticeably less, since the temperature of the sample did not rise above 130 – 215°C. Another feature of the multipulse and direct current effect is a sharp decrease in the uniform deformation of titanium and an increase in deformation localization, which is especially manifested in ultrafine-grained titanium.

In contrast to multi-pulse and direct current, the mode of single pulses in coarse-grained titanium promotes strengthening and a noticeable increase in plasticity (curve *2*, Fig. 4*a*). It can be assumed that the physical nature of such hardening is low-cycle deformation. Note that strengthening, as the effect of exposure to the current, is an anomalous phenomenon for pure metals, since in almost all known articles, the authors record only a decrease in flow stresses, i.e., softening. It is likely that in this work the anomalous strengthening effect became possible due to such a regime of titanium recrystallization, in which a very large grain size was formed. This fact is consistent with the strengthening in a single crystal of aluminum, reported by the authors of the work [21].

In ultrafine-grained titanium this effect is not observed, probably due to high flow stresses. A similar phenomenon has already been noted for the Ti-7Al alloy [22], where the authors associate hardening with a change in the dislocation mechanism of deformation: from sliding to climb of dislocations under the action of a current. The effect of the current depends on the mode: it is stronger with higher energy of the injected current, which increases with the transition from single current pulses to multi-pulse and direct current.

Another feature of the stress-strain curves under the action of single current pulses is the appearance of stress jumps downwards, the amplitude of which decreases from 50 MPa for coarse-grained titanium to 25 MPa and less for ultrafine-grained titanium. Since there is practically no thermal effect for this current mode (Table 1), it can be argued that the electroplastic effect really exists and it decreases with decreasing grain size.

Interestingly, stress jumps were observed not only in the plastic deformation zone, where they are appearing due to the interaction of moving dislocations with conductive electrons. Similar jumps,

Table 2. Mechanical properties under tension for coarse-grained and ultrafine-grained Ti

Structure state	Current mode	Drop amplitude, MPa	Current duration, sec	Heat effect, °C	UTS, MPa	El, %
Course-grained	Without current	—	—	RT	450	33.0
	Single pulses	25 – 50	<0.1	30	480	40.0
	Multipulse current	—	270	130	370	13.7
	Direct current	—	234	130	255	12.7
Ultrafine-grained	Without current	—	—	RT	1010	7.0
	Single pulses	5 – 20	<0.1	30	995	6.0
	Multipulse current	—	102	160	815	5.0
	Direct current	—	96	160 – 215	435	4.5

but poorly recorded due to much smaller amplitude (about 5 MPa), are also present in the elastic part of the stress-strain curves. Since there are no free dislocations during elastic deformation, it can be assumed that the cause of the appearance of stress jumps is the thermal effect and, as a consequence, the expansion and dilatation of the sample.

Finally, we note the asymmetric shape of shocks, the form of which indicates different mechanisms of softening and hardening in the jump itself. An almost instantaneous stress drop is caused by an ultrafast current pulse, and the subsequent stress rise is due to the relatively slow cooling of the sample.

CONCLUSION

1. It is shown that cold rolling in calibers of commercially pure titanium, accompanied by a pulsed current, makes it possible to achieve a maximum degree of 90 % without destruction, and subsequent annealing in the range of 500 – 700°C is capable of forming structure states in a wide range of grain sizes from 0.5 to 50 μm with strength from 450 to 1010 MPa.

2. Changing the current mode introduced during tension from single pulses to multipulse and direct current increases the contribution of the thermal effect to the decrease in flow stresses in comparison with the non-thermal electroplastic effect.

3. The manifestation of the electroplastic effect in titanium is controlled by the grain size, a decrease in which leads to its degradation and, as was shown earlier to complete disappearance in the amorphous state due to a decrease in free dislocations density.

Acknowledgments

This research was funded by the Ministry of Science and Higher Education of the Russian Federation, the contract 075-15-2021-709, unique identifier of the project RF-2296.61321X0037 (equipment maintenance).

The author declares no conflict of interest.

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