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Stress jump behavior during tensile deformation assisted by pulsed current

V. V. Stolyarov

vlstol@mail.ru

Mechanical Engineering Research Institute of the Russian Academy of Sciences, Moscow 101000, Russia

Abstract: The article is related to the study of the manifestation of the athermal electroplastic effect in the form of stress jumps on the stress-strain curve on a number of conductive materials. The aim of the work is to discover the relationship between the microstructure of the material, pulsed current modes and parameters of the stress jump, including its shape, amplitude and duration. For comparison, studies were carried out on materials that differ greatly in thermal and electrical conductivity, grain size, and amorphous-crystalline state. The methodological basis of the study was quasi-static tensile tests, accompanied by the introduction of single pulses of unipolar current of high density and duty cycle at a constant pulse duration. The high duty cycle of the pulsed current during the tension process ensured that the temperature of the samples was maintained close to room temperature. The relationship between the structure-phase state, phase transformations and grain size in the materials with the main parameters of the stress jump is shown. In a coarse-grained state, a pulsed current of high duty cycle can lead to simultaneous strengthening and increased ductility, possibly due to low-cycle strengthening. Structural refinement of alloys leads to a decrease in the electroplastic effect until it disappears in the amorphous state. In shape memory alloys that exhibit an austenitic-martensitic transformation upon heating, the direction of the stress jump changes to the opposite direction compared to the traditional one. Fractographic studies of the fracture surfaces of samples tested with and without current did not reveal structural changes, confirming the athermal nature of the electroplastic effect under the selected pulsed current modes. It is assumed that the results of the study can be used to verify various models of the electroplastic effect, as well as to select pulsed current modes to increase deformability during metal forming without significant heating.

Keywords: metals, alloys, tension, electroplastic effect, pulse current, stress jump

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1. Introduction

It is known that the interaction of electric current and plastic deformation in conductive materials is accompanied by the electroplastic effect (EPE) [1, 2, 3]. It is assumed that one of the mechanisms of this phenomenon may be the interaction of conduction electrons with the elastic fields of dislocations [4]. Depending on the type and modes of current, EPE manifests itself in strain curves in two ways. When using direct or pulse current of low duty cycle ($Q \leq 500$) EPE leads to a noticeable decrease in flow stress and often to an increase in plasticity characteristics (reduction of area, elongation to failure) under uniaxial tension [4]. Due to the significant increase in temperature by hundreds of degrees, it is classified as a thermally activated effect, in which the mechanical response of the material approaches that of conventional heating. This is probably why a number of researchers have claimed that EPE is absent in copper, iron, and other materials [5, 6]. When using high-duty pulse current ($Q \geq 1000$), EPE manifests itself in the form of downward stress jumps, each of which corresponds to a single current pulse [7]. Since the temperature of the material changes slightly, EPE is referred to as the athermal effect or pure EPE [8].

This article focuses specifically on this type of EPE, which makes it possible to separate the thermal effect from the purely electroplastic one. Another reason for using pulsed current with increased duty cycle is the ability to avoid intensive neck formation and, as a consequence, an increase in current density and thermal heating.

Many EPE studies were performed using direct current throughout the tensile test and, as a consequence, were accompanied by a strong thermal effect [9]. To reduce the temperature of the sample, the authors began to use cooling with air, liquid nitrogen or introducing direct current in the form of short pulses. For example a study of EPE upon introduction of one direct current pulse with a duration of 0.5 s was performed for the Mg alloy AZ31 [10]. In pure metals (titanium, iron, lead, tin) the authors also studied the amplitude of stress jumps from the action of EPE using the single-pulse method [11]. Common to such studies is the use of short current pulses ($t = 20 - 300$ μs) with a high duty cycle. Thus in titanium alloys Grade 4 and VT6 the authors used a pulsed current with a duty cycle in the range $(5 - 20) \times 10^3$ to compare the thermal and athermal contributions [12]. The high sensitivity of mechanical behavior to microstructure and pulse current of higher duty cycle 5×10^4 was demonstrated in [13] for aluminum alloy A6016 in different structural states.

At the same time it is the basis of many high-strength structure aluminum alloys that require increased deformability. The first studies of EPE in coarse-grained aluminum under the influence of single current pulses were carried out in [14] where it was shown that the maximum relative stress jump amplitude of 7% was achieved at the highest current density of 370 A/mm^2 and the lowest strain rate of 3.3×10^{-4} s^{-1}. Later, in article [15] for technically pure aluminum AA1050 in a partially annealed state under tension accompanied by direct current the effect of EPE was not only confirmed, but also its dependence on the stress-strain state was shown.

Of particular interest is the study of the possible influence of grain size over a wide range on the EPE in different materials. Such studies for aluminum were carried out in [14, 7,16], which, however, are difficult to compare due to different experimental conditions. In [14], using a pulse current density of 1000 A/mm^2, it was shown that increasing the grain size from 100 μm to a single crystal helps to double the stress jump amplitude. In [16], when single current pulses with a density of 450 A/mm^2 were introduced the authors observed the opposite effect, as a decrease in the jump amplitude in single crystalline aluminum compared to a polycrystalline alloy. In [7], the study of EPE was carried out only on an aluminum bicrystal at a high current density of 1600 A/mm^2 and a pulse duration of 1 ms.

The purpose of the article is a phenomenological analysis of stepwise deformation accompanied by a pulse current in several conductive materials and to identify the relationship between microstructural features and stress jump parameters.

2. Materials and methods

The objects of study were conductive metals and alloys that differ significantly in electrical resistivity: commercially pure aluminum AD 1, commercially pure titanium VT1-0, as well as shape memory alloys $Ti_{49.3}Ni_{50.7}$. Using thermal and deformation-thermal treatment methods structural states differing in grain size were formed: a single crystal $50\times50\times50$ mm^3 in size from high-purity aluminum obtained by melting under zero-gravity conditions; coarse-grained (CG) aluminum with grain size D=120 μm in the form of a rod annealed at a temperature of 500°C; ultrafine-grained (UFG) aluminum (D=0.5 μm) obtained by severe plastic deformation [17]; coarse-grained (D=25 μm) and UFG (D=0.3 μm) titanium, obtained by annealing and ECAP, respectively; the shape memory alloy was obtained in CG (D=40 μm) and nanostructured (NS) (D=50 nm) states, respectively, by quenching at a temperature of 700°C and electroplastic rolling [18]. Mechanical tensile tests were performed on flat samples with a gage zone size of $1\times2\times10$ mm^3 (for bulk workpieces) and $0.04\times2\times10$ mm^3 (for quickly quenched strips) on an IR-5081-20 machine at room temperature and a tensile speed of 1 mm/min. The temperature of the samples during the tension process was recorded by a thermocouple in the center of the sample with an accuracy of ±2°C.

Tension started after the introduction of a pulse current and the fixing of temperature. The pulse current parameters were chosen so that downward stress jumps were consistently observed. The pulse duration in all cases was 1 ms, the duty cycle was in the range $(5-25)\times10^3$ and the current density j slightly exceeded the critical value j_{cr} for a given material. The stress jump parameters were estimated by the maximum amplitude Δσ (MPa), duration Δt (ms) and asymmetry coefficient $K_a=t_2/t_1$, where t_1 and t_2 are the times of the descending and ascending branches of the stress jump in milliseconds. The stress jump over time was recorded with a time resolution of 200 ms. To ensure the reliability of the experimental results tensile tests were performed on three samples.

3. Results

3.1. Tension

Below are stress-strain curves without current and with current (Fig. 1a, b, c) and the corresponding stress jumps (Fig. 1d, e, f) for aluminum AD1 in different structural states.

At the moment the current pulse is introduced the flow stress instantly and significantly jumps and when the current is turned off it is restored but noticeably more slowly. The ascending part of the jump exhibits the usual strain hardening. Quantitative parameters of stress jumps, temperature and mechanical characteristics are given in Table 1. Note that in Fig. 1c for UFG aluminum at a current density of 450 A/mm^2 the curve is not shown because has no jumps and completely coincides with curve 1 for tension without current. However increasing the current density to 2000 A/mm^2 leads to the appearance of jumps (curve 2). Visual observation of the stress jumps confirms a change in their shape and magnitude associated with a change in the microstructure of aluminum (Fig. 1d, e, f).

It can be seen at the same current density of 450 A/mm^2 the stress jump amplitude is maximum in the single crystal (≈2.5 MPa, Fig. 1d), has an intermediate value in CG aluminum (≈ 0.5 MPa, Fig. 1e), and there are no jumps in UFG aluminum at the same current density. Structure refinement of the aluminum affects the duration Δt and the asymmetry coefficient of the stress jump K_a. Thus the transition from a single crystalline to an UFG structure increases the duration and asymmetry coefficient, respectively, from 300 to 1200 ms and from 1 to 4 (Table 1).

It can be assumed that at the same current density a decrease in the grain size in aluminum by three orders of magnitude leads to a decrease and disappearance of the EPE, as well as to an increase in the asymmetry of the stress jump.

Similar observations of stress jumps in stress-strain curves during tension without current and with current were performed for titanium VT1-0 (Fig. 2 a, b) and a shape memory alloy based on the TiNi composition (Fig. 3 a, b) in different structure states.

In titanium at current densities of 250 and 470 A/mm^2, the stress jump amplitude was 31 and 25 MPa, respectively, in the CG and UFG states (Fig. 2 c, d). As in aluminum, the shape of the stress jump is asymmetric with K_a increasing to 12 and 6, respectively, in the CG and UFG states.

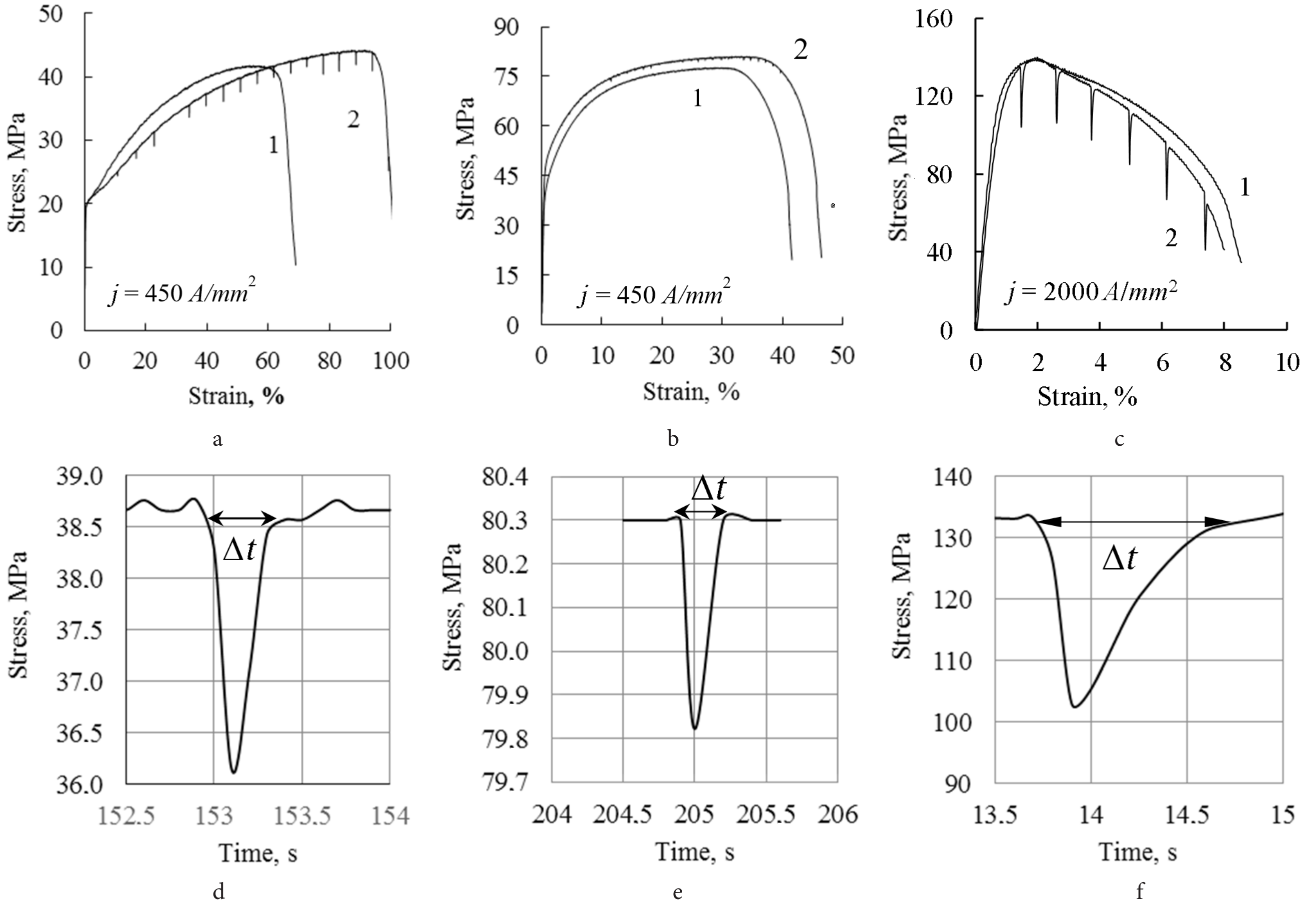

Fig. 1. Stress-strain curves (a, b, c) and type of stress jumps (d, e, f) for aluminum in state: single crystal (a, d); CG polycrystal (b, e); UFG (c, f). 1 — no current; 2 — with current.

Table 1. Stress jump parameters and mechanical properties of materials.

Materials	Grain size, μm	Current density A/mm²	T, °C	Amplitude Δσ, MPa	Δt, ms	K_a	UTS, MPa	YS, MPa	El, %
Al	single crystal	no current	23	-			41.6	19.4	64.4
		450	23	0.5 – 3.0	300	1.0	44.0	19.5	97.5
	120	no current	23	-			77.5	34.0	40
		450	23	0.5 – 2.0	400	2.0	80.8	48	45
	0.5	no current		-	-		137	120	8.0
		450	23	no			137	120	8.0
		2000	31	30	1200	4.0	137	120	7.5
Ti	25	no current	23	-	-		450	250	30
		250	23	30 – 35	12500	12	490	250	40
	0.3	470	<50	25	6500	6	1005	650	6
$Ti_{49.3}Ni_{50.7}$	40	no current	23	-	-		650	425	20
		500	41	168	14000	13	650	425	20
	0.05	500	<50	11	10000	10	1100*	-	-
TiNiCu	amorphous	500	<50	1	500		1100*	-	-

*fracture stress

In the $Ti_{49.3}Ni_{50.7}$ alloy, the direction of the jumps with the introduction of a current density of 500 A/mm² changes to the opposite (Fig. 3a, b), the stress jump amplitude is 168 and 11 MPa, the shape of the jump remains asymmetric with K_a=13 and 10, respectively, for the CG and UFG states (Fig. 3c, d, Table 1).

It is interesting the UTS and El for titanium and aluminium in the CG state under tension with current were higher than under tension without current (Table 1).

3.2. Fracture surface observation

Studies of fracture surfaces using scanning electron microscopy of samples after tension without current and with current in the form of single high-density pulses on selected materials and states have shown that the ductile nature of the fracture and the initial size of the dimples or cleavage do not change. And only a low duty cycle current led to an increase in the size of fracture dimples from 1–2

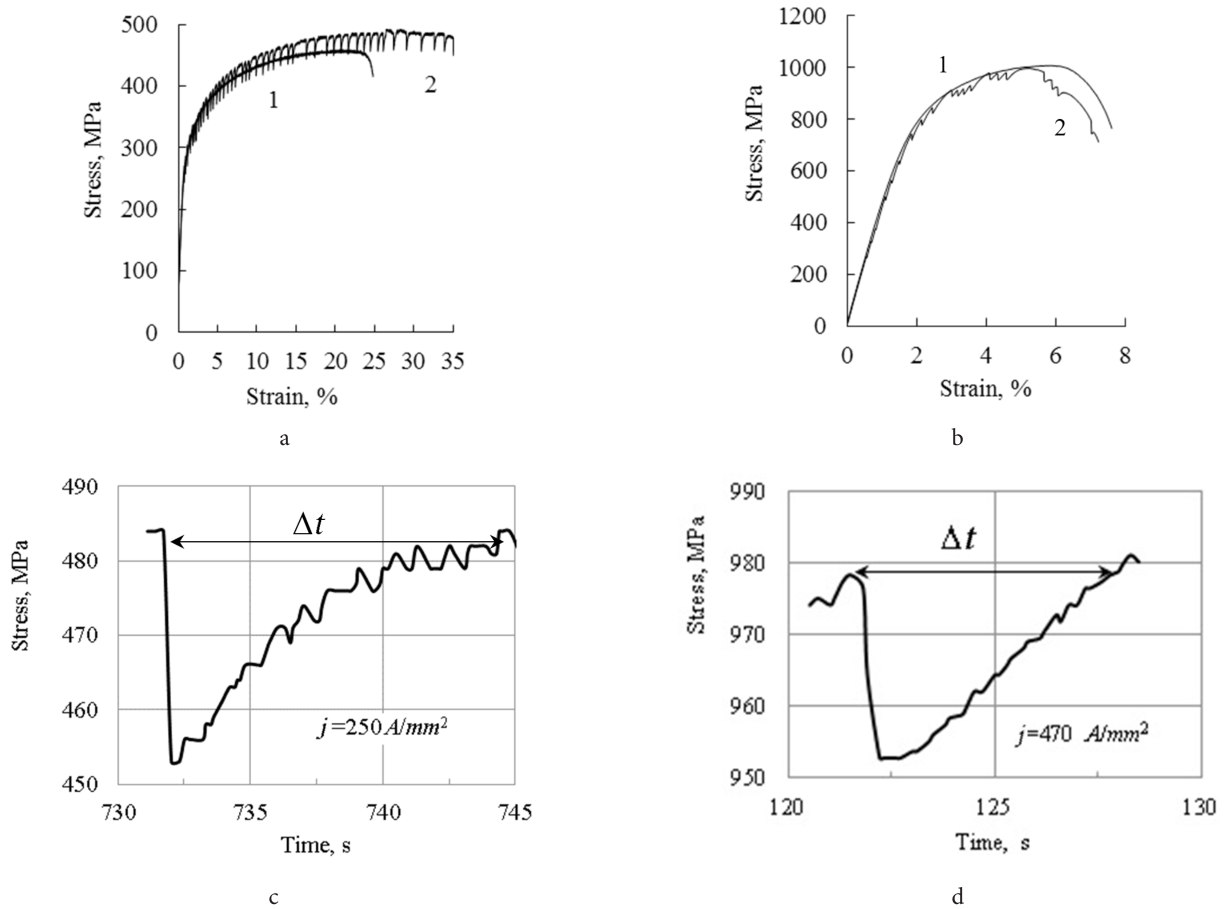

Fig. 2. Stress-strain curves (a, b) and type of stress jumps (c, d) for titanium in the state: CG (a, c); UFG (b, d). 1 — no current; 2 — with current.

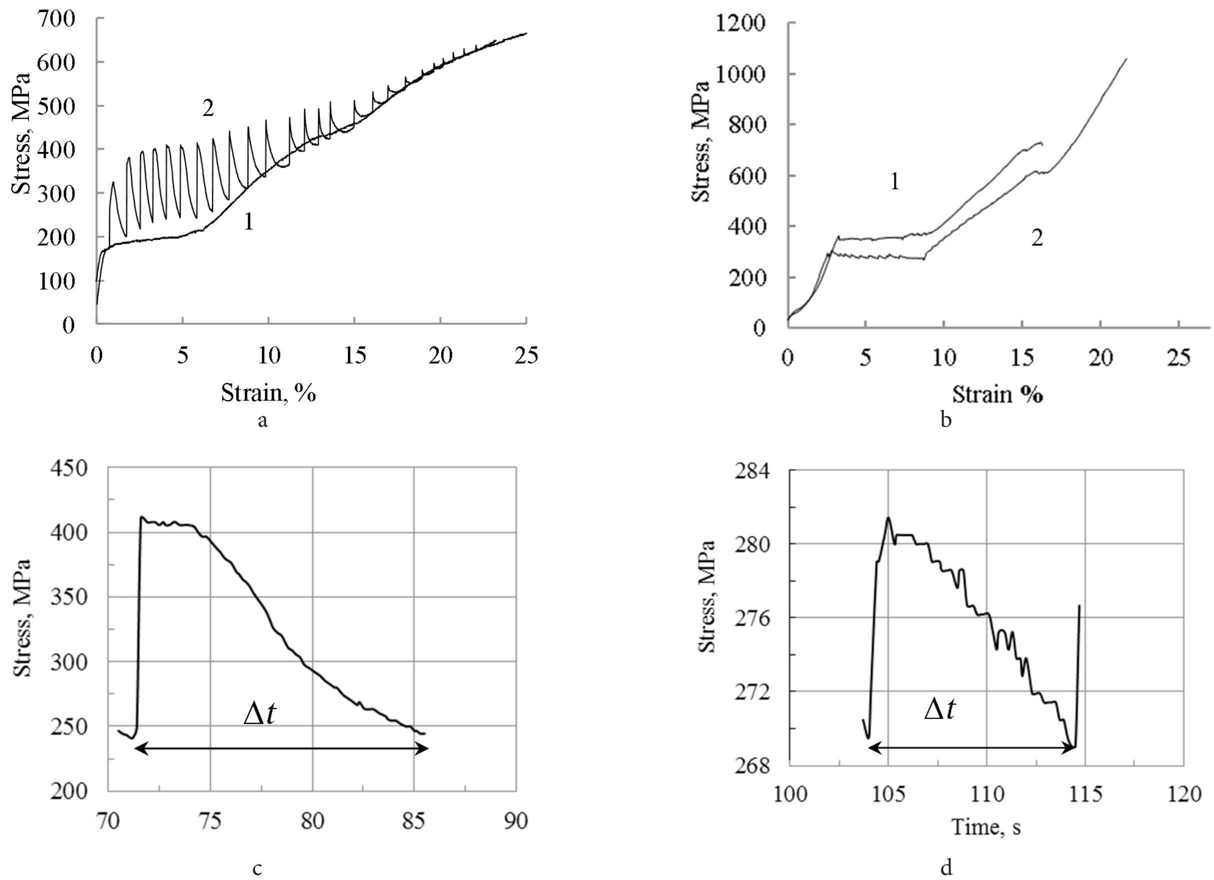

Fig. 3. Stress-strain curves (a) and type of stress jump (b) for TiNi alloy in the state: CG (a, c); UFG (b, d). 1 — no current; 2 — with current.

to 5–10 μm in the NS $Ti_{49.3}Ni_{50.7}$ alloy (Fig. 4a, b) but to a decrease in the size of honeycomb-shaped dimples from 1 to 0.5 μm in CG aluminum alloy D16 (Fig. 4c, d).

4. Discussion

Unlike similar works performed earlier, this article examines the influence of single current pulses that do not lead to high thermal effects. Contrary to the established opinion in the literature on the increase in plasticity at tension accompanied by electric current, in most of our studies we recorded a noticeable decrease not only in strength, but also in elongation to failure and associated this phenomenon with the intense necking under multi-pulse current [12].

Data on mechanical properties under the influence of single current pulses in Table 1 indicate a simultaneous increase in strength and ductility for single crystal and polycrystal aluminum. This effect is not observed in UFG aluminum and titanium. One of the reasons for the increase in strength and ductility may be low-cycle hardening in each current pulse that leads to micro deformation preventing the formation of a neck.

As can be seen from Fig. 1d, e, f; Fig. 2c, d; Fig. 3c, d the stress jumps caused by single current pulses are characterized by shape, stress amplitude, duration and direction up or down. It turned out the shape of the jump is asymmetric as a rule. This is agreed with data for steel, aluminum and magnesium alloys [19, 20, 13, 10]. That is the ratio of recovery time and stress decay t_2/t_1 can vary widely depending on the material, its structure state, current mode, etc. For example, in an aluminum single crystal the stress jump has a symmetrical shape (K_a=1) but in polycrystalline metals and alloys the stress jump has an asymmetric shape and K_a can be an order of magnitude larger (Table 1). It is assumed that the *asymmetry of the stress jump* is to a lesser extent associated with different heat transfer mechanisms when a current pulse is introduced and switched off, but to a greater extent with strain hardening during stress recovery. In particular, this is confirmed in an aluminum single crystal, in which the movement of dislocations during relaxation and subsequent hardening occurs in one slip system in the absence of high-angle grain boundaries. As a result, the shock shape is symmetrical. In an aluminum polycrystal, the presence of grain boundaries that are non-transparent for dislocations leads to dislocation inhibition and corresponding strain hardening, which is the cause of the shock asymmetry.

The *stress jump amplitude* Δσ is mainly related to the current density and varies from 0.5 to several tens and even hundreds of MPa. The condition for the appearance of jump is $j > j_{cr}$ [2] at which a larger current density corresponds to a larger stress jump amplitude. As for the jump duration it is related to the thermal conductivity of the material and increases as it decreases. The data in Table 1 demonstrate an increase in the stress jump duration from hundreds of milliseconds for highly thermally conductive aluminum to several seconds for titanium and its alloys having low thermal conductivity.

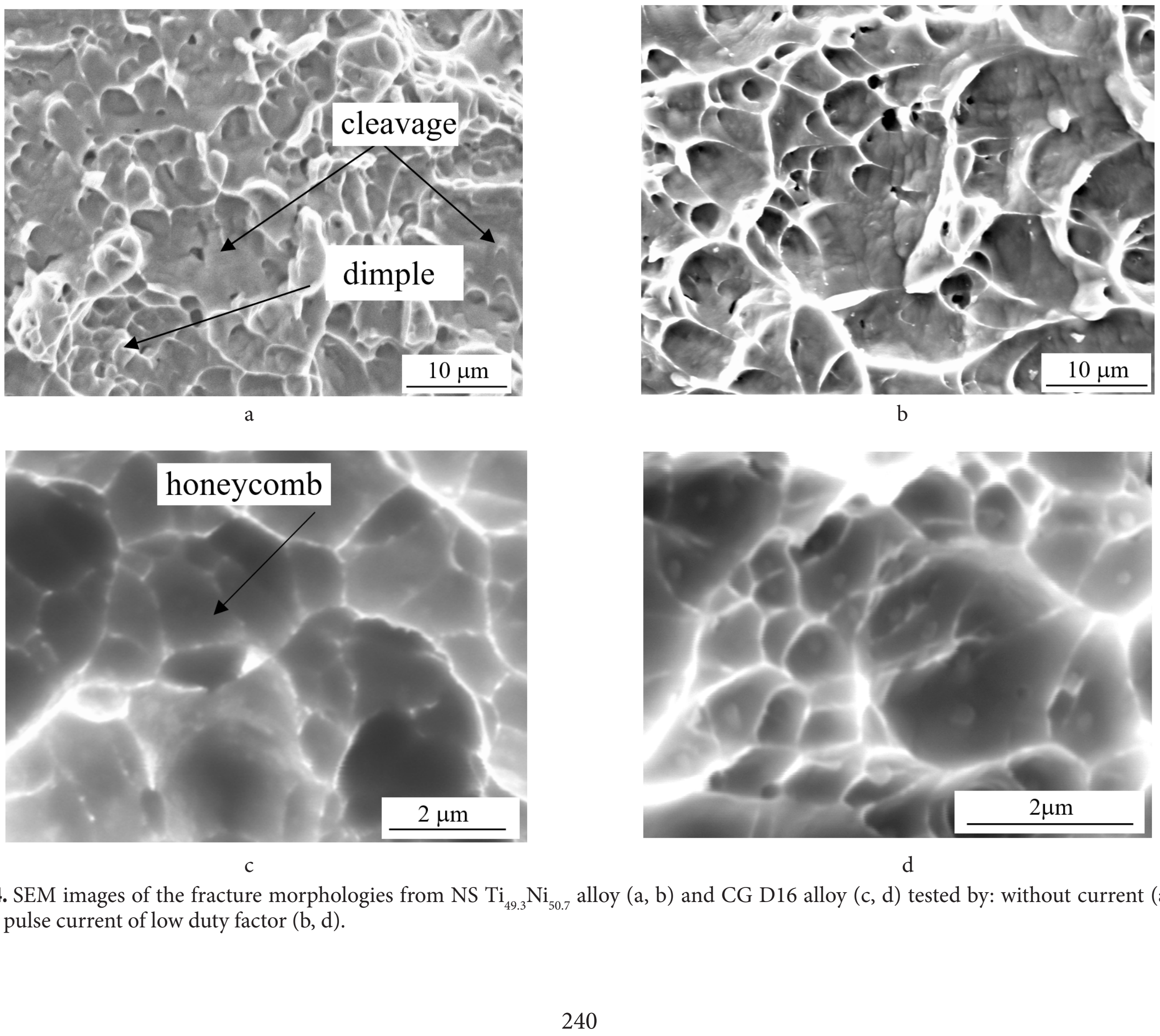

Fig. 4. SEM images of the fracture morphologies from NS $Ti_{49.3}Ni_{50.7}$ alloy (a, b) and CG D16 alloy (c, d) tested by: without current (a, c); with pulse current of low duty factor (b, d).

It is shown that the *stress jump direction* can be not only downward but also upward. An example is a shape memory alloy in which the flow stress increases by almost 170 MPa (Fig. 3). The unusual behavior of the alloy is due to the manifestation of the martensitic transformation of austenite into martensite even with low heating. Stress jumps show a decreasing trend in Δσ in a structure with a finer grain size at the same current density. This is consistent with the results of [21] which showed the disappearance of EPE in the amorphous state of TiNiCu alloys and its appearance during nanocrystallization. Thus, in a shape memory alloy at the same current density $j = 500$ A/mm^2 the stress jump amplitude decreases from 168 to 1 MPa.

Fractographic studies did not reveal differences in the fracture surfaces of samples strained without current and with single current pulses of high duty cycle. The failure mode was consistent with the ductile type in both cases. Only in the case of applying a multi-pulse current with a low duty cycle could slight differences in the shape and size of the dimples and cleavages be observed. Note that the dimples size in the austenitic NS $Ti_{49.3}Ni_{50.7}$ alloy increased while in the coarse-grained D16 alloy it decreased. It can be assumed that the opposite change in the size of the dimples is associated with the thermal effect of a low duty cycle pulsed current. For a single-phase NS austenitic $Ti_{49.3}Ni_{50.7}$ alloy the thermal effect in the form of an increase in temperature to 100°C logically leads to weak grain growth and, as a consequence, to the growth of fracture cells. For a coarse-grained D16 alloy the same effect can lead to artificial aging with the release of second-phase particles and, as a consequence, fragmentation of the microstructure.

A phenomenological study of the characteristics of stress jumps under the influence of single current pulses has important practical applications. Quantitative characteristics of jumps can be used in modeling physical mechanisms and verifying the proposed models. Of particular importance are data on the stress jump duration of surges in different materials which guide EPE consumers to a reasonable choice of the duty cycle of the pulsed current. Finally, the grain size in metal alloys subjected to deformation under current conditions must be taken into account when assigning technological regimes during metal forming.

5. Conclusions

– Stress jumps in tensile diagrams caused by the athermal electroplastic effect are a source of information about the interaction of current and plastic deformation of metallic materials. The parameters of a stress jumps are closely related to the physical properties and structure-phase state of the material, as well as the pulsed current mode.

– An increase in the asymmetry and duration of a stress jump correlates with a decrease in the thermal and electrical conductivity of metals and alloys. The change in the direction of the downward-upward jump in a metastable shape memory alloy corresponds to the phase transformation of martensite to austenite.

– The amplitude of the stress jump increases with increasing grain size in the material and increasing current density.

– Increasing the duty cycle of the pulse current allows to change the type of electroplastic effect from thermal to athermal, helping to increase technological deformability.

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