Вісник ХНУ, серія «Фізика», вип. 25, 2016. с. 12-15

УДК 538.945:539.214
PACS: 83.50. – v Deformation and flow of metals
83.60. Wc Instability of flow

The influence of electrical current pulses on the plastic deformation of copper

O.S. Mazitov, S.V. Lebediev

V.N. Karazin Kharkov National University
Svoboda square, 4, Kharkov, Ukraine, 61022

The paper studied the influence of electrical current pulses with density of 300 – 900 A/mm^2 and duration of $4\cdot10^{-4}$ s on the plastic deformation of the technically pure copper. The deformation curves under and without the influence of current pulses during the deformation of specimen were obtained. The comparison of obtained curves was carried out. It was determined that the passing of electrical current pulses during the deformation of copper leads to the resource of plasticity growing.
Keywords: electroplastic effect, plastic deformation, electrical current pulses.

В роботі вивчено вплив імпульсів електричного струму густиною 300 – 900 А/мм^2 та тривалістю $4\cdot10^{-4}$ с на пластичну деформацію технічно чистої міді. Були отримані деформаційні криві при впливі та без впливу імпульсів струму в процесі деформації зразка. Було виконано порівняння отриманих кривих. Встановлено, що проходження імпульсів електричного струму при деформації міді приводить до зростання ресурсу пластичності.
Ключові слова: електропластичний ефект, пластична деформація, імпульси електричного струму.

В работе изучено влияние импульсов электрического тока плотностью 300 – 900 А/мм^2 и длительностью $4\cdot10^{-4}$ с на пластическую деформацию технически чистой меди. Были получены деформационные кривые при воздействии и без воздействия импульсов тока в процессе деформации образца. Было выполнено сравнение полученных кривых. Установлено, что прохождение импульсов электрического тока при деформации меди приводит к возрастанию ресурса пластичности.
Ключевые слова: электропластический эффект, пластическая деформация, импульсы электрического тока.

Introduction

It is known that lattice defects and deformation conditions (such as strain rate and temperature) influence on the mechanical properties of metal. But also the influence of phonons and electrons of conductivity on dislocations motion exists. It is possible to affect on the crystal by the flux of high-energy electrons in the electric current pulse [1, 2]. The phenomenon of sharp reduction of resistance to deformation of the metal and growing of plasticity by passing of current pulses is called the electroplastic effect. It is stated that the critical value of the electric current density exists and above that value the picture of deformation changes qualitatively and it cannot be explained only by influence of temperature and (or) magnetic field. When the direction of the drift velocity of electrons is along the direction of external force there is the maximum effect [3].

There is a big amount of experimental results at this time which demonstrate the influence of the electrical current pulses with large densities on the plastic flow of pure metals and alloys [4]. In available works it was found that the electroplastic effect is observed when the drift velocity of electrons is higher than velocity of dislocations motion. However, issues that deal with a lattice heating and controlling the phenomenon on the microscopic level remain outstanding.

In this context, it might be useful to study this phenomenon at higher densities of electric current considering the Joule's heating and other related exposures on the deformable specimen. It will allow to separate the influence of thermal and athermal processes on the deallocation of dislocations from stoppers and their displacement in the crystal lattice [5].

Object and methodology of the experiment

To carry out the tasks assigned in the work copper specimens were used. Impact on the object was carried out by the external load, temperature, electrical current pulses. Tests were carried out by the universal testing machine, which had the next technical characteristics:

- creating loads on the specimen up to $2\cdot10^3$ N with ultimate sensitivity of 10^{-2} N;
- registration of elongation during active loading with sensitivity of $5\cdot10^{-6}$ and relative deformation of $5\cdot10^{-2}$ %;

- strain rate range of $10^{-6} – 10^{-2}$ s^{-1}.

For research a roll of technically pure copper wire with diameter of 0,8 mm was made in factory. While the preparation the wire was cut into segments with length of 50 mm and in order to reduce the number of defects in the specimens created by rolling the annealing with temperature of 450°C and vacuum of 10^{-2} mm was made.

Electric current pulses generator which created single and multiple pulses with current up to 1 kA, duration of ~10^{-5} – 10^{-4} s and voltage of 65 - 400 V was used in experiment. Discharger with frequency of 400 – 1250 Hz also was used in the work. To make experiments with annealed lattice defects during passing of pulses we need to have a big drifting velocities of electrons with density of $10^3 – 10^4$ A/mm^2 and duration of 10^{-4}– 10^{-6} s.

Electric scheme consists of the next elements: 1 – control block; 2, 3 – thyristors; 4 – inductor; 5 – specimen; 6 – capacitor bank; 7 – voltmeter; 8 – standart resistance of 1 mOhm; 9 – oscilloscope; 10 – load resistor; 11 – capacitor bank of 20 mF; 12 – 220 V supply; 13 – transformer; 14 – diode bridge.

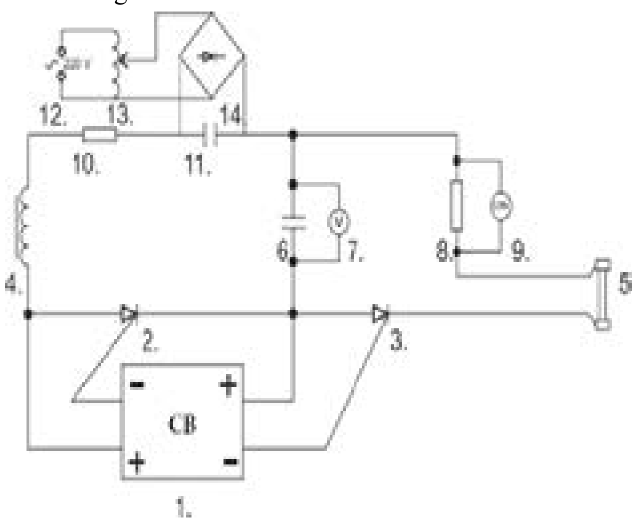

Fig.1. Electric scheme of the pulse machine.

Relation of current and duration that is shown on fig.2 is regulated by changing the voltage on supply. Calibration of pulses by amplitude and duration is carried out by Rigol DS1052D oscilloscope. In addition, the graphic image of electric current pulse was carried out (fig.3).

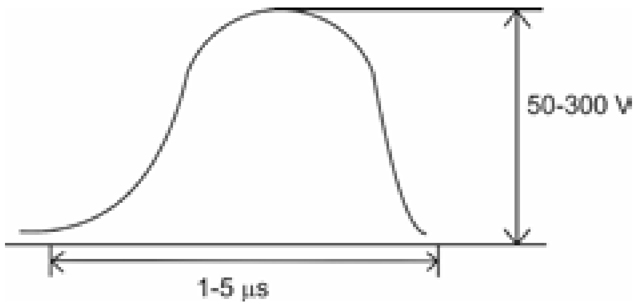

Fig.2. Single pulse curve in voltage – tome coordinates.

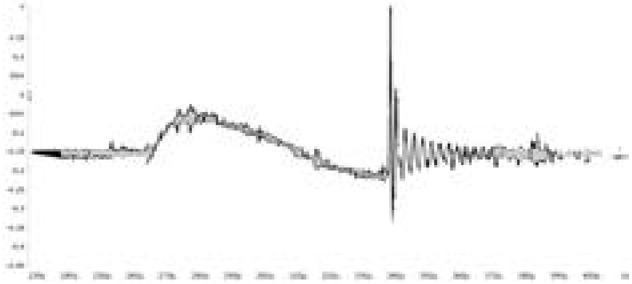

Fig.3. The scan of the electric current pulse in time.

Main scheme characteristics: current of (0,1 - 10)·10^3 A; working voltage of 60 – 450 V; pulse duration of (1,4 - 18)·10^{-5} s; bell-shaped pulse; steepness of the front and slope are 4·10^6 and 2·10^5 kA/s respectively; the smallest duty cycle in automatic turning on mode is of 1 s.

Results and discussion

To define the influence of electric current pulses on deformation characteristics of metal the loading curves in coordinates load P – time t, obtained without (j=0) and with the electric current pulses (j≠0), were compared (fig.4).

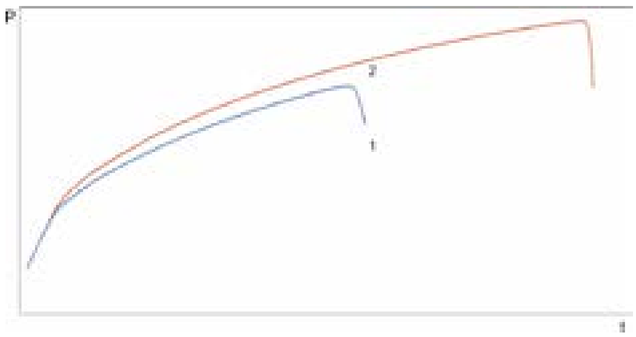

Fig.4. The load – time diagram in the area of elastic and plastic loading of copper specimens with diameter of 0,8 mm without (1) and with (2) electric current pulses.

The initial area of P(t) curve of the polycrystalline copper (99,5 %) without electric pulse exposure (dependence 1) allows to define: the effective elastic modulus in the specimen – moving rod of loading machine system (<E>), yield stress (σ_0), strain hardening coefficient ($\theta = d\sigma/d\varepsilon$). The electric current pulses exposure on the

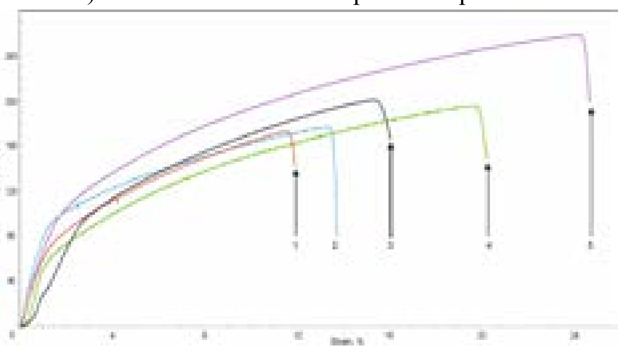

Fig.5. Deformation curves under different values of densities of electric current (1 – 0 A/mm^2, 2 – 291 A/mm^2, 3 – 500 A/mm^2, 4 – 708 A/mm^2, 5 – 916 A/mm^2).

elastic and plastic area of loading curve is shown on fig.4 (dependence 2).

It is already known that there is no clear explanation how electric current pulses influence on plastic deformation of metals and alloys.

Examples of the influence of electric current pulses in continuous mode on deformation curve character of polycrystalline copper specimens are shown on fig.5. As can be seen, electric current pulses of different density influence on deformation curve character in different ways.

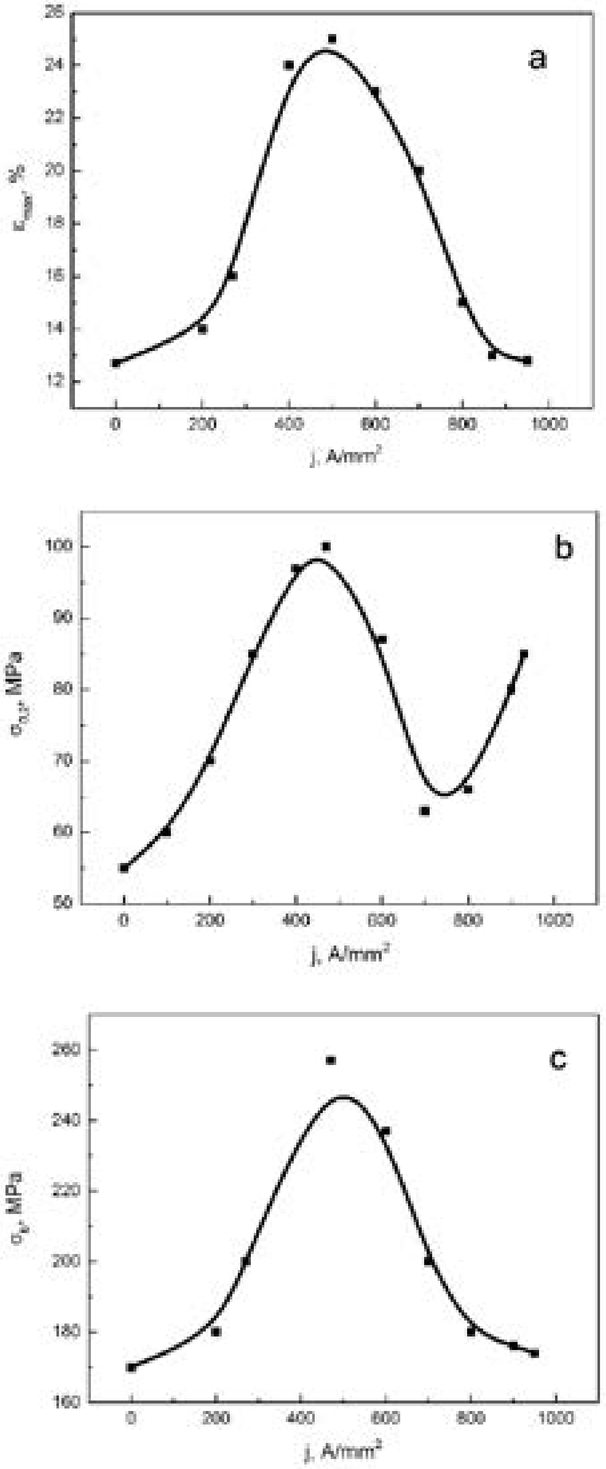

Fig.6. The dependencies of strengthening characteristics on electric current density, a – plasticity resource, b – conditional yield stress, c – ultimate tensile strength.

Let us consider the influence of electric current density on mechanical characteristics of copper. Dependencies $\varepsilon_{max}(j)$, $\sigma_{0,2}(j)$, $\sigma_b(j)$ are shown on fig.6 respectively, where ε_{max} – plasticity resource, $\sigma_{0,2}$ – conditional yield stress, σ_b – ultimate tensile strength.

As can be seen from these three figures, ultimate tensile strength, plasticity resource and conditional yield stress are increasing non-monotonously and the maximum is observed at j = 500 A/mm^2. It is also noteworthy that plasticity resource and ultimate tensile strength at 900 A/mm^2 are approximately equal to the value when there is no exposure of electric current pulses whereas conditional yield stress with current density higher than 700 A/mm^2 increases rapidly.

It can be seen from graphics that with current density up to 500 A/mm^2 both ultimate tensile strength and plasticity resource increase which is abnormally. This effect, supposedly, occurs in the result of exposure of electric current pulse that influence on dynamics of the dislocations motion. Probably, that with passing of electric current pulse the velocity of dislocations motion increases, whereas with its absence velocity decreases and dislocations are starting to concentrate in the specimen. Thus, the specimen becomes stronger.

In addition, the role of adiabatic heating was considered. Let us evaluate the temperature increase of the copper specimen with unit volume from the relation:

$$\Delta T = (\rho \cdot \langle\tau\rangle \cdot c_p^{-1} \cdot D^{-1}) \cdot \langle j\rangle^2, \qquad (1)$$

where specific electrical resistance $\rho = 1{,}73\cdot10^{-8}$ Ohm·m (without temperature dependence); duration of pulse at the level of $0{,}7\cdot j$ is $\langle\tau\rangle = 10^{-2}$ s; specific heat capacity $c_p = 3{,}85\cdot10^2$ J·kg^{-1}·K^{-1} (without temperature dependence); density $D = 8{,}93\cdot10^3$ kg·m^{-3}. Then, for current density values of (291 and 916) · 10^6 A/m^2 temperature increase ΔT will be 2,1 and 20,6 K respectively.

While electric current pulses are passing through, some of the electrons interact with atoms of crystal lattice causing the latter to oscillate with frequencies higher than phonons have. Such oscillations are called breathers [6]. When the flux of electrons passes through the crystal lattice, the latter starts to shake. Therefore, dislocations continue their motion and do not accumulate near the stoppers. In the result of dislocations motion the plasticity of specimen grows, that can be seen on fig.4 (a). After definite moment (j = 500 A/mm^2) the plasticity starts to decrease. This is explained by the strengthening of specimen at high densities of dislocations.

Conclusions

1. The influence of electric current pulses on plastic deformation of the technically pure copper with temperature

of 300 K is shown.

2. It was stated that with determined density (j=500 A/mm^2) the maximum value of plasticity resource and ultimate tensile strength is observed.

3. It was found out that values of strengthening characteristics with current of 900 A/mm^2 approximately coincide with the values when there are no electric current pulses.

References

1. O.A. Troitskiy. Technical physics letters 10, 18 (1969).
2. A.F. Sprecher, S.L. Mannan, H.Conrad. Acta Metall. 34, 7, 1145 (1986).
3. V.I. Spitsin, O.A. Troitskiy elektroplasticheskaya deformatsiya metallov – Moskva: Nauka, 1985. – 160 p. – In Russian.
4. O.A. Troitskiy, Yu.V. Baranov, Yu.S. Avramov, A.D. Shlyapin. Fizicheskie osnovyi i tehnika obrabotki sovremennyih materialov. M.- I., (2004). 590 s.
5. V.P. Lebedev, S.V. Savich. Vestnik HNU. Seriya: Fizika 962, v.15, 88 (2011).
6. Dubinko V.I. Reaction – rate theory with of the crystal anharmonicity / V.I. Dubinko, P.A. Selyshchev, J.F.R. Archilla // Physical Review E. – 2011. – Vol. 83, № 041. – P. 124 – 137.