DOI 10.2478/ama-2018-0039 acta mechanica et automatica, vol.12 no.4 (2018)

ELECTROPLASTIC DEFORMATION BY TWINNINGMETALS

VLADIMIR V. SAVENKO*

*Physics and Engineering Faculty, Mozyr State Pedagogical University
named after I.P.Shamyakin, 28 Studencheskaya Str., 247760, Mozyr, Republic of Belarus

savenko-vl@rambler.ru

received 1 March 2018, revised 15 October 2018, accepted 18 October 2018

Abstract: The article deals with theoretical and experimental approaches to electroplastic deformation caused by twinning of metals. The author specifies physical fundamentals of Kinetics regarding the development of twinning caused by the excitation of electronic subsystem of metals. Physical models of new channels for the realization of twinning aroused under conditions of electroplasticity have been discussed. Mechanisms of plasticized influence of a surface electric charge have been defined as well as the contribution of a dynamic pinch-effect in the elastic plastic deformation of metals with the participation of the intrinsic magnetic field of the current. The dynamic pinch effect creates ultrasonic vibration of the lattice system while Kinetics changes and plastic deformation are stimulated increasing the amplitude of the oscillations of rectilinear dislocations and the periodic change in the position of the dislocation loops with an increase in the probability of detachment of dislocations from the stoppers. When deformed above the yield point and due to the pinch effect the intrinsic magnetic field of the current diffuses into the crystal where the diffusion rate depends both on the conductivity of the metal and on the frequency of the current. It is necessary to take into account the physical conditions for the creation of ponderomotive effects in relation to specific technically important materials for the practical use of electroplastic deformation technology, especially when processing metals with pressure.

Keywords: Electroplastic Deformation, Ponderomotive Action Current, Pinch Effect, Skin Effect, Pulse Current, Magnetic Field, Electric Field Vortex Field Hall, Mechanical Pressure, Maximum Axial Force

1. INTRODUCTION

Development of Modern Physical Material as a science is closely associated with the development of technological processes of deformation for metals caused by the pressure found under the conditions of electroplasticity with the aim to obtain technically important materials with high characteristics that ensure their application in extreme physical conditions.

Electroplasticity found in metals is implemented by passing short pulses of high density current of 10^3A/mm^2 with a duration of 10^{-4}s, during plastic deformation through electrically conductive materials, which is known as the electroplastic effect (EPE).This effect is universal and manifests itself in all materials under different types of plastic deformation by sliding (magnesium steel) and twinning (bismuth).

EPE stimulates deformation processes, reduces strain forces, energy consumption and improves the physical and mechanical characteristics of the material.

Several authors explain the mechanisms of electroplastic deformation in the course of sliding by electron-dislocation interaction, the pressure of the "electronic wind" on the accumulation of dislocations, point defects, decrease in starting stresses for dislocation disruption from the stoppers, the action of thermal and nonthermic effective stresses and also the spin softening of metals (Troitskiy and Savenko, 2013; Khrushchev et al., 2017; Troitskiy, 2008b; Stashenko et al., 2008).

It should be noted when a current pulse is excited in the metal deformation zone, a significant amount of Joule heat is released, with a pulse duration equals to 100μs and a current density equals to 100 to several thousand A/mm^2, heating the sample does not exceed several degrees if the pulses are separated intervals equal to tens of seconds.

Plastic deformation by twinning is carried out when the slip is impossible, for example, while orientational inhibition at high loading rates and at low temperatures. The twinning begins at stress concentrators, the development of twins is carried out at high velocities. The concentration of stresses and deformations at the boundaries of twins often lead to the destruction of the material.

Thus, if it was possible to control the development of twinning, there would be a real opportunity to use twinning as a reservoir of material plasticity if to reduce the concentration of stresses at the boundaries of twins. Furthermore the twin boundaries are natural obstacles to complete dislocations, that’s why it is possible to strengthen the material in an effective way by means of a system of thin twins.

2. EXPERIMENTAL METHODS, RESULTS AND DISCUSSION

When electric current pulses pass through metal single crystals with density equals to 50-1000 A/mm^2 and duration equals to 10^{-4}s, a redistribution of deformation by twinning is observed in the vicinity of the stress concentrators. If the crystal is deformed by a diamond indentor and current pulses are passed before or after deformation, no effect is observed. The constant electric field imposed on the crystal at any stage of deformation is also not effective. However, if the electric current pulse is passed through the crystal during deformation, the pattern of the indenter print

DOI 10.2478/ama-2018-0039

changes significantly. The print on the left is obtained after 10 seconds of holding the crystal with an indentor load of 10g. The imprint on the right corresponds to the same exposure and load to the indenter, but 5 seconds passed the load was lowered, a current pulse 10^{-4}s was passed through the sample. The current density in the pulse was 600 A/mm^2.

Comparison of the strain patterns with the current pulse and without a pulse shows that under the combined effect of electrical and mechanical stresses, the plastic deformation is stimulated by twinning. The length of individual twins increases, new twins appear. Thus, all the side factors affecting the deformation conditions were excluded.

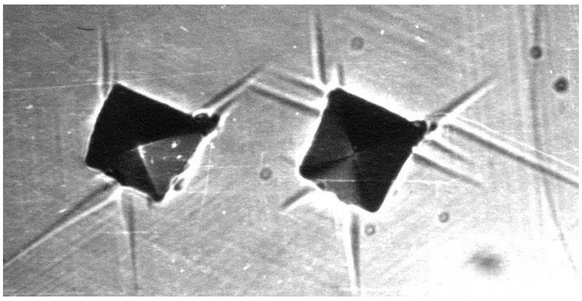

Fig. 1. A photomicrograph of twins on the cleavage plane of bismuth single crystals, x 530. The print on the left was obtained with an indentor load of 10 g. The imprint on the right – with the same load on the indenter, but during deformation through the crystal a current pulse of density 600 A/mm^2.

An increase in the density of total dislocations in the crystal leads to a decrease in volume of twinning and the area of the double.

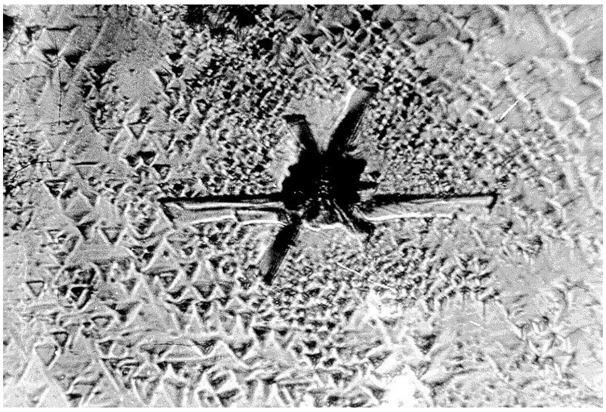

Fig. 2. The etched plane (111) of a bismuth crystal after deformation by a concentrated load. (Load on the indenter 10g; x530)

An increase in the density of total dislocations in the crystal leads to decrease in the volume of twinning and the area of the double boundaries (Fig. 2).

With increasing voltage applied to the crystal during deformation, the range and generation of twinning dislocations increases (Fig. 3). Up to a voltage of 800 V, the excitation processes of dislocation sources are preferable. The increase in voltage leads to the predominance of the following stages in the development of twins: the formation of a surface of separation and the translation of twinning dislocations along the final interface of the twins.

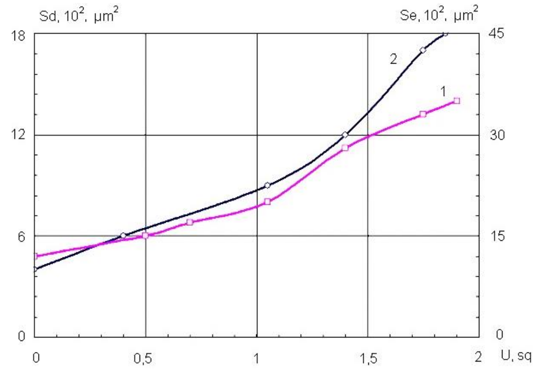

Fig. 3. Run (I) and generation of twinning dislocations (2) on the stress in bismuth crystals:Sd is the area of the twinning interface; Se is the volume of the twin boundaries; U is the electrical voltage applied to the crystal.

If we compare the twins obtained from the action of a concentrated load, and the twins that arise when the load and the electric current pulse are combined, it is easy to see that the ratio of the thickness of the twins at the mouth to their length h/L differs. The ratio h/L characterizes the degree of incoherence of the twin boundaries. If we divide this value by the crystal lattice parameter in the direction perpendicular to the motion of the twinning dislocations a, we obtain the average density of twinning dislocations at the interfaces:

$$\rho_d = \frac{h}{aL}, \tag{1}$$

instead of: a – lattice parameter.

The linear density of twinning dislocations for doubles caused by the combined effect of electrical pulses and mechanical stresses is 10^3-10^4 cm^{-1}, for doubles arising without current pulses, this value is 2-5 times larger (Fig. 2).

As the voltage is increased, the density of the twinning dislocations decreases, i.e. the deviation of the twin boundaries from the twinning plane decreases. With the curvature of the interfaces of twins, brittle fracture is often associated. Cracks in the vicinity of the twin boundaries usually arise when there are significant deviations of the boundaries from the twinning plane. There is a decrease in the degree of incoherence of twin boundaries, and thus there is a density of twinning dislocations at the boundaries; it is primarily a decrease in the thickness of dislocation clusters, a decrease in the role of the double boundaries as concentrators of internal stresses and, as a result, a decrease in the probability of crack formation at the boundaries of twin strips.

The study of a large number of prints shows that the ratio of the load on the indenter to the square of the maximum length of the twin beam in prints is a value close to a constant value. The values of P/L^2_{max} with the change in load almost do not change for crystals of the same composition. P/L^2_{max} has the dimensionality of stresses and characterizes the linear dimensions of the region of the crystal that extends beyond the twinning, so it is natural to assume that this value is proportional to the voltage needed to advance the twinning dislocations in the crystal, thus the quantity P/L^2_{max} can serve as a quantitative characteristic for the plastic deformations are twinning. The ratio P/L^2_{max} is proportional to the stresses at which the motion of the twinning dislocations ceases, when the dislocation at the apex of the twin reaches the regions where the external stress from the concentrated load is balanced by the resistance forces of the crystal lattice, i.e. this is an analog of the yield stress for plastic deformation by twinning. The order of variation of P/L^2_{max} corresponds to the ranges of starting voltages for twinning dislocations in crystals (Stashenko, 2008; Troitskiy, 2008a; Gorelik, 2008; Gorelik and Zlobina, 2008; Samuilov and Troitskiy; 2017).

Fig. 4 shows the dependence of P/L^2_{max} on the current density in the pulse. We can see that P/L^2_{max} values begin to fall at current densities in the pulse of 50-70 A/mm^2 (the threshold values of the electroplastic effect in twinning), then the P/L^2_{max} value decreases significantly and at high current density in the pulse, of the quantity P/L^2_{max}.

If we consider the effect of electric current pulses on the development of twinning, then the P/L^2_{max} values under simultaneous action of external load and current pulse decrease several times, i.e. the transmission of the current pulse at the time of loading of the crystal is accompanied by a significant decrease in the resistance of the crystal lattice to twinning. Thus, the one-time action of the load and electrical impulses makes it possible to plasticize the material further due to twinning. In this case, the electric current pulses increase the share of twinning in the total plastic deformation of the doubling materials, i.e. increase the plasticity reserve.

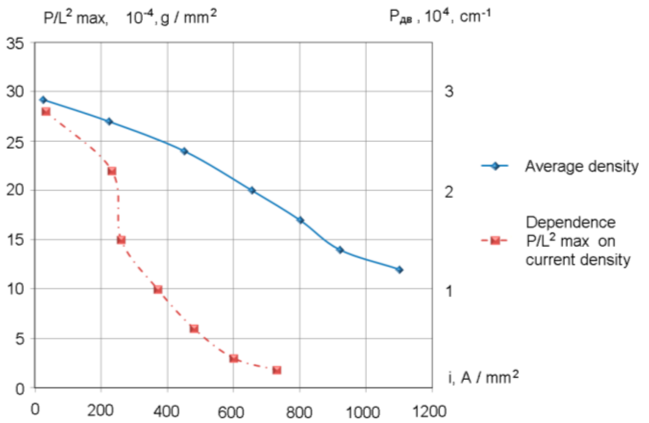

Fig. 4. Dependences of the value of P / L^2_{max} on the current density and the average density of twinning dislocations on the current density in bismuth Bi- 99.99%.

The branching of twins always appears on the curve boundaries where the degree of incoherence of the twin boundaries is the greatest.

Twins usually appear on dislocation clusters and lead to relaxation of internal stresses at the imprint. Up to now, it has been known that relaxation of internal stresses can be achieved by developing slip i.e. in the areas of the crystal adjacent to the twin boundaries (Gorelik and Zlobina, 2008). In this paper for the first time it was discovered that under the action of electrical pulses, the relaxation of internal stresses occurs as a result of the development of new twins, with new twins arising not only on clusters of complete dislocations, but also at the boundaries of the twin interlayers, i.e. on clusters of twinning dislocations what was experimentally and theoretically shown by the author in the work Troitskiy and Savenko (2013). Doubles, emerging at stress concentration sites, discharge dislocation clusters, thereby reducing the likelihood of brittle fracture in the stressed places of the crystal lattice (Fig. 5).

To explain this we use the picture of stress fields in a wedge-shaped twin (Fig. 6), which was obtained on the assumption that the twin boundary consists of complete (Khrushchev et al., 2017; Samuilov, 2017; Surkaev, 2015) rather than partial dislocations. The stress fields around the accumulation of such dislocations, which have the form of a wedge, can be calculated as shown in the formula:

$$\sigma_{xy} = \frac{Gb}{2\pi(1-\nu)}\left\{\sum_{n=0}^{N_1}\frac{(x+nd)[(x+nd)^2-(y+nh)}{[(x+nd)^2+(y+nh)^2]^2} + \right. \tag{2}$$

$$\left. + \sum_{n=0}^{N_2}\frac{(x+nd)[(x+nd)^2-(y-nh)^2]}{[(x+nd)^2+(y-nh)^2]^2}\right\},$$

where: σ_{xy} –the shear stresses, b –is the Burgers vector modulus, G – is the shear modulus, ν – is the Poisson ratio, n – is the summation index, N_1 and N_2 – are the number of dislocations at the twin boundaries (Troitskity and Savenko, 2013).

In our case, computer-generated curves were taken N_1=N_2=10.

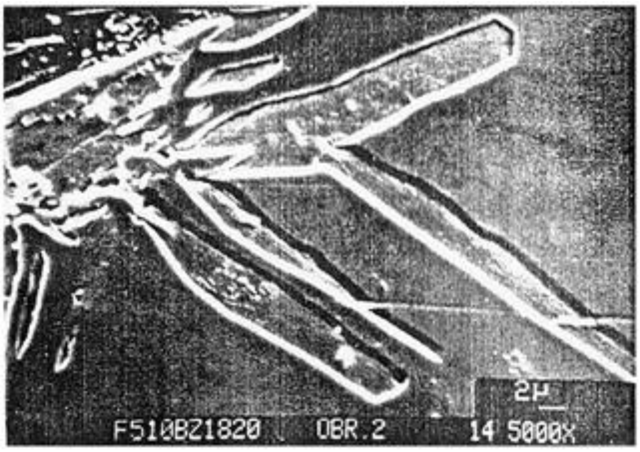

Fig. 5. The branching of a double as a result of the presence of an obstacle in the translation path of twinning dislocations.

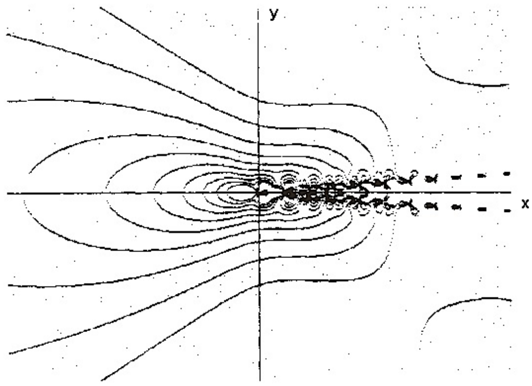

Fig. 6. Stress fields for a wedge-shaped twin.

As it is shown in Fig. 6 the stresses increase with the approach to the twin boundary, moreover, at the double vertex they are of the same order as in the immediate proximity of the twin boundary, but at a distance two or three times larger.

As a result, in the presence of stoppers in the path of motion of the wedge-shaped twin, a redistribution of the stresses at its vertex occurs in such a way that the magnitude of their projections to a new twinning direction becomes comparable with the threshold value of the appearance of the twin.

DOI 10.2478/ama-2018-0039

The growth of the density of complete dislocations makes twinning difficult.

In authors'opinion, consideration of the most probable mechanisms of the influence of electromagnetic fields on the plastic deformation of metals should be carried out with due regard to the state of the surface of the crystal, since the excitation of the electronic subsystem of the crystal by an electromagnetic field leads to a change in its surface energy. In deformation processes, moving dislocations, interacting with a free surface, acquire excess free energy, become unstable and tend to reach the surface of the crystal (Skal, 2013; Krajewski et al., 2012).The edge dislocation is attracted to the surface by the force of the "mirror image", which is determined by the slowly varying logarithmic potential. At the same time, the output of dislocation to the surface is accompanied by the appearance of a characteristic step. In this case, energy is created to create a new cellγb^2 where $\gamma$is the surface energy. This force is distributed deep into the crystal by a half-width of a dislocation of the order of several b, and in the immediate vicinity of the surface it can predominate over the "mirror image" force. Therefore, a decrease in the surface energy of the metal will facilitate the release of dislocations of the same sign onto the surface and lead to an increase in the rate of plastic deformation and a decrease in the deformation hardening. At the same time, the increase in surface energy intensifies the work of surface sources of dislocations by compensating for the "mirror image" force.

Dislocation is a linear defect only from the point of view of distortion of the electronic structure of the material, which is formed on the edge of the superfluous half-plane. It is to be expected that bound electronic states arise here, whose energy spectrum and the corresponding wave functions differ from the energy spectrum and the wave functions of the external valence electrons of a defect-free crystal lattice.

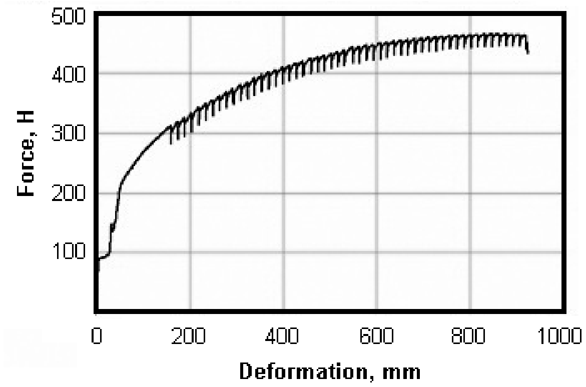

Fig. 7. Dependence of the statistical force applied to the sample on the magnitude of deformation up to the moment of its destruction. Stainless steel under the influence of current pulses

The excitation of the electronic subsystem of the current pulse metal, when electroplasticity is realized in a metallic sample loaded above the yield point, leads to the appearance of additional deformation processes due to the oscillations of the deforming forces, ponderomotive effects occur during the deformation processes (Fig. 7) which cause vibroacoustic ultrasonic vibrations of the crystal lattice in different crystallographic directions (Fig. 8) (Troitskity and Savenko, 2013; Khrushchev et al., 2017) due to the appearance of dynamic pin - and the skin effect.

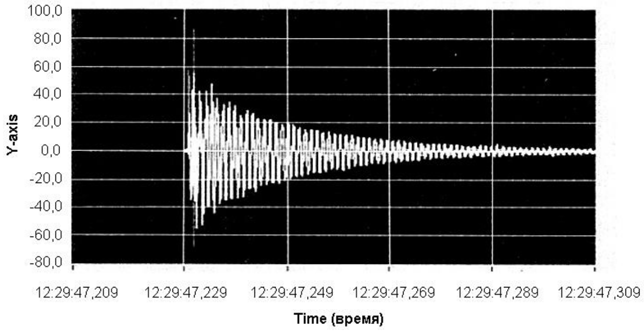

Fig. 8. Transient processes of ultrasonic acoustic vibration from the action of current pulses under strain conditions above the yield point.

If we consider the "ionic", "covalent", "metallic" bonds from the point of view of the distribution of the wave functions of the external valence electrons, then there is a clear tendency to delocalization of wave functions and an increase in the degree of their overlap. In this vein the greater overlap of the wave functions of the valence electrons of the atoms composing the crystals and the electronic states at the dislocations, the more plastic is the given material. The excitation of the electron subsystem of the crystal leads to an overlap of the wave functions in the dislocation core and to an increase in its mobility. The introduction into the impurity crystal where the wave functions of the valence electrons are delocalized, it reduces the shear stresses and, as a result, facilitates the process of plastic deformation is observed.

Under the influence of the intrinsic magnetic field of the current, which envelops the conductor (a deformable sample) with annular lines, polarization of the electronic subsystem of the metal arises and, as a result, the appearance of a transverse electric Hall field that prevents further compression of the electron plasma.

Consider the equation $\frac{\partial \mathrm{H}}{\partial \mathrm{t}} = \frac{\mathrm{c}^2}{4\pi\sigma\mu\nabla^2\mathrm{H}}$, which agrees with the diffusion equation $\frac{\partial n}{\partial t} = D\nabla^2 n$.

Choosing the projection on the Z-axis, we write in the form:

$$\frac{\partial H_z}{\partial t} = \partial M \frac{(\partial^2 H_z)}{\partial x^2}, \tag{3}$$

where: $\partial \mathrm{M} = \frac{\mathrm{c}^2}{4\pi\sigma\mu}$ – coefficient of magnetic diffusion, c – electrodynamic constant, μ – magnetic permeability, σ – specific conductivity.

Since, the field outside the sample varies according to the harmonic law, the following Z projection of the magnetic field inside the sample will be:

$$H_Z(0,t) = H_0 \cos(\omega t), \tag{4}$$

where magnetic field strength on the boundary, for $x = 0$. The harmonic dependence (3) characterizes the so-called stationary skin effect (Troitskiy, 2008a).

Since equation (2) is linear and contains real coefficients, the following calculations can be simplified by going over to complex writing. Thus, we seek a solution of another auxiliary problem with the replacement of $\cos(\omega \mathrm{t})$ by a complex exponent:

$$H_Z(0,t) = H_0 e^{(-i\omega t)}. \tag{5}$$

The solution of the original problem with a real field can be obtained from the solution of the auxiliary problem with a complex field by separating the real part. Since the magnetic field outside the sample is proportional to$e^{-i\omega t}$,we assume that the solution of the auxiliary problem should be sought in the following form:

$$H_Z(x,t) = H(x)e^{(-i\omega t)}. \qquad (6)$$

Substituting this dependence (4) in the partial differential equation (2), we can obtain the ordinary differential equation (3):

$$\frac{\partial^2 H}{\partial x^2} = -\frac{2i}{\delta^2} H, \qquad (7)$$

where: $\delta = \sqrt{\left(\frac{2D_M}{\omega}\right)} = \frac{c}{\sqrt{2\pi\sigma\mu\omega}}$has the dimension of length.

The general solution of an ordinary differential equation of the second order with constant coefficients is in the form of a sum of exponentials Ae^{ikx} with constant coefficients A and k^2.The coefficientkis found by substitution e^{ikx} into equation (6).The algebraic equation $k^2 = \frac{2i}{\delta^2}$, hastworoots $k = \pm\frac{(1+i)}{\delta}$.

One of them, $(k+)$ corresponds to the decreasing, and the other($k\ -$) to the alternating magnetic field, which grows to the axis of the sample (as $x \to \infty$) to the alternating magnetic field. The radially increasing magnetic field should be omitted, since it corresponds to a meaningless increase in the magnetic field up to an infinite value when moving away from the source. Thus, within the conductor the solution of the auxiliary problem has the form:

$$H_z(x,t) = Ae^{-\left(\frac{(1-i)x}{\delta}\right)}e^{(-i\omega t)}. \qquad (8)$$

The coefficient A can be found from the condition of continuity of the tangential projection of the magnetic field strength at the sample boundary at $x = 0$.Since the strength of the magnetic field varies outside the conductor at $x = 0$ according to the law $H_z(0,t) = H_0 e^{-i\omega t}$, we conclude that $A = H_0$. Consequently,

$$H_z(x,t) = H_0 e^{-\left(\frac{(1-i)x}{\delta}\right)}e^{(-i\omega t)}. \qquad (9)$$

Defining the real part of the complex function $H_Z(x,t)$, we find the real magnetic field in the sample:

$$H_z(x,t) = H_0 e^{-\frac{x}{\delta}} cos\left(\omega t - \frac{x}{\delta}\right), \qquad (10)$$

where: δ – thickness of the skin layer (Troitsky, 2007; Savenko, 2017; Savenko et al., 2017).

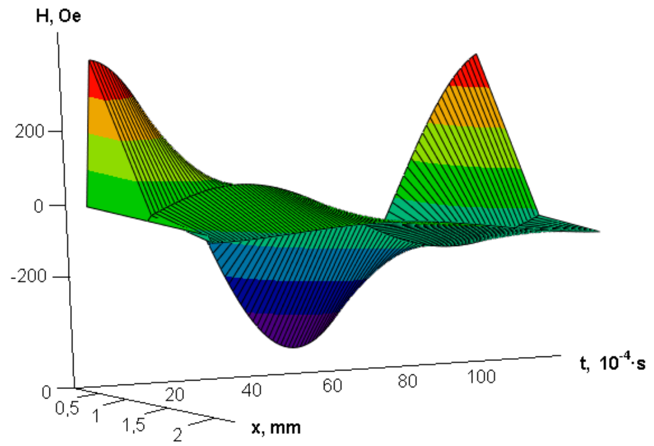

Fig. 9. The change in the magnetic field in a sample of magnesium at $\nu = 600Hz$

To determine the value of the magnetic field arising from ponderomotive factors during electroplastic deformation by 35 transition rolling of magnesium samples, we use the MathcadProfessional program, taking into account the final parameters of the last transition of deformation magnesium: $s = 4\ \mathrm{mm}^2$ – cross-sectional area of the sample, $r = 2\ \mathrm{mm}$ – sample cross-section radius, $j = 10^3\,\frac{A}{mm^2}$ – current density, pulse duration $\tau = 10^4 s$, frequency $\nu = 600\ \mathrm{Hz}$, $\sigma = 22{,}7 \times 10^3\ \mathrm{cm/mm}$ – conductivity of magnesium.

As we can see in the graph (Fig. 9) a change in the magnetic field is observed in the sample of deformation magnesium with final parameters at the last transition.

The intensity of the magnetic field increases while moving from the center to the sample surface and it reaches the value H=400 Oe (31830 A/m) being at a distance of 1 mm from the center of the cross section of the sample, the magnetic field strength is H=100 Oe(7957A/m).

3. CONCLUSIONS

1. Electron-plastic deformation stimulates the formation of the interface, and the translation of the twinning dislocations along the finished interface, increases the range and generation of twinning dislocations which opens the possibility of additional plasticization of the twinning material, increasing the share of twinning in the total plastic deformation, thereby increasing the plasticity reserve of the doubling materials.
2. The twinning in the region of twin boundaries leads to an intense multiplication of the twinning dislocations and to the collective interaction of the screw components of the twinning dislocations with an obstacle, which opens up new channels for the realization of twinning.
3. Excitation of mechanical twinning by external field not only influences plasticizes, but also increases the real strength of the material. The stimulation of twinning by current pulses leads to a decrease in the density of twinning dislocations at the interfaces of mechanical twins, equalization of their dislocation structure, acceleration of stress relaxation processes, which reduces the probability of brittle fracture in the region of twin boundaries.
4. The electric charge arising on the surface of the sample as a result of the Hall polarization facilitates the operation of dislocation sources and stimulates the translation of twinning dislocations along the finished interfaces, leads to a partial discharge of long-range elastic stresses in clusters of twinning dislocations and the appearance of new channels for realizing the process of plastic deformation by twinning.

REFERENCES

1. **Gorelik V. S., Zlobina A. I.** (2008), Spectra of secondary radiation of opal matrices filled with silver nanoparticles obtained by fiber-optic excitation, *Inorganic material*, 44, 7, 6–9.
2. **Gorelik V.S.** (2008), Excitation by semiconductor LEDs secondary radiation in opals with pores filled with silver nanoparticles, *Inorganic material*, 44, 1, 1–4.
3. **Gorelik, V. S., Zlobina A. I., Chanieva R. I.** (2008), Spectra of secondary radiation of opal matrices filled with silver nanoparticles obtained by fiber-optic excitation, *Inorganic material*, 44(7), 6–9.

DOI 10.2478/ama-2018-0039

4. **Khrushchev M.M., Troitskiy O.A., Stashenko V.I., LevinI.S.** (2017), Change in the phase composition of steel under the influence of current pulses and microwave radiation under deformation, *Ferrous metallurgy,* 7, 82–87.
5. **Khrushchev M.M., Troitskiy O.A., Stashenko V.I., LevinI.S.** (2017), The Effect of current pulses and microwave radiation on the phase composition of steel under deformation, *Mechanical engineering and engineering education*,1, 50–56.
6. **Krajewski, A.,Włosiński W., Chmielewski T., Kołodziejczak P.** (2012), Ultrasonic-vibration assisted arc-welding of aluminum alloys, *Bulletin of the Polish Academy of Technical Sciences,* 60 (4), 841–852.
7. **Samuilov S.D.** (2017),Electroplastic compaction (briquetting) of dispersed conductive materials for recycling waste of high-strength alloys, obtaining blanks, semi-finished products, materials and products with a new level of properties, *Fundamental and applied problems of engineering and technology,*4(324), 83–89.
8. **Samuilov S.D.,Troitskiy O.A.** (2017), New methods of production of porous metal materials with closed and open porosity, *Fundamental and applied problems of engineering and technology,* 3(323), 12–16.
9. **Savenko V.S.**(2017), The contribution of ponderomotive factors to the realization of electroplastic deformation / V.S. Savenko, O.A. Troitsky, A.G. Silivonets // Izvestiya NAN RB,*A series of physical and technical sciences*, 1, 85–91.
10. **Savenko V.S., Silivonets A.G., Gunenko A.V.** (2017), Calculation of current density and magnetic field strength inside a conductor under conditions of electroplasticity, *Vesnik of the Polotsk State University, Series C. Fundamental sciences,*4,72–78.
11. **Savenko V.S.,Troitskiy O. A., Gunenko A.V.** (2018), Physical Aspects of Electroplastic Deformation of Metals, *Vesnik of the Brest University*, 1, 40–48.
12. **Skal A.S.** (2013), The full Lorentz force formula responsible for turbulence in solids and fluids and explained Faraday's paradox, *International Journal of Scientific & Engineering Research*, 4(2), 10–14.
13. **Stashenko V.I.** (2008), Electroplastic drawing of medium carbon steel, *Problems of mechanical engineering and reliability of machines,* 6, 12–14.
14. **Stashenko V.I., Troitskiy O.A., Novikov N.N.** (2008), Electroplastic drawing of iron wire, *Problems of mechanical engineering and reliability of machines,* 5, 32–38.
15. **SurkaevL.** (2015), Magnetohydrodynamic perturbations arising in metallic conductors under the action of the discharge current, *Technical Physics,*60(7), 981–993.
16. **Troitskiy O.A.** (2007), Influence of current Pulse count in Pulse Train and time Lag Between Pulses on the Electroplastic metal Deformation, *Symposium China-Rassia "Elektroplastic effect in metals"*,China, 28–32.
17. **Troitskiy O.A.** (2008), Electronic mechanisms of electroplastic deformation of metals, *Deformation and fracture of materials*, 5, 41–44.
18. **Troitskiy O.A.** (2008), Inertial effect of the Stewart-Tolman for high-speed wire drawing and the collision of the bullet with the target, *Problems of mechanical engineering and reliability of machines*, 9, 29–34.
19. **Troitskiy O.A.** (2016), *Physical and technological basis of electro-plastic deformation of metals*, MGPU, Mozyr.
20. **Troitskiy O.A., Savenko V.S.** (2013), *Fundamental and applied researches of electroplastic deformation of metals: monograph*, Ministry of Finance ITC, Minsk.