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MODELING THE TREATMENT OF HIGH-ENERGY PULSED ELECTROMAGNETIC FIELD OF THE MICRO-CRACKS IN A POLYCRYSTALLINE METAL

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ABSTRACT

The paper studies electroplastic effect in terms of the hypothesis of the healing of defects in the material under the influence of high-energy pulsed electromagnetic fields. The processes occurring in the metallic samples under the impact of electrical current of high density are considered. The electric, temperature fields, stress-strain state and phase transformations in the vicinity of micro-defects with line size 10 microns are studied. Such defects are always present between the grains in a polycrystalline metal after metallurgical casting or appear in it during its deformation under processing.

The coupled quasi-stationary model of the impact of high-energy electromagnetic field on the pre-damaged electroplastic material with an ordered system defects are proposed. The model accounts for melting and evaporation of the metal and the dependence of its physical and mechanical properties on the temperature. The problem is solved numerically by finite elements method with adaptive mesh using on the base of alternative Euler-Lagrange's method. The boundary value problem is solved for a representative element material with a micro-defect in the case of plane strain. The micro-defects in the form of flat cracks with rounded tips are considered.

The presence of micro-cracks leads to inhomogeneous physical and mechanical fields in the material. Numerical modeling has shown that in the vicinity of the micro-defects intensive electromagnetic field and current with large fields gradients arise. This causes rapid local heating in the vicinity of the tip of the micro-crack, followed by thermal expansion of metal, and subsequently melting the material. The inhomogeneous heating results in a high compressive stresses and intense plastic flow of the material in the vicinity of micro-crack. The resulting stress field is not only closing the shores of micro-crack, but also reducing its length and ejecting the metal into the crack. Ejection occurs through the formation of the metal jet of molten metal directed into the crack. These processes may be accompanied not only by melting in the vicinity of the tip, but also evaporation of the metal to crack for the micro-cracks located near the outer boundaries of the sample.

The simultaneous reduction in the length, the ejection of the molten metal into the cracks and closing of micro-crack shores leads to the fact that the shores of the crack come into contact with the jet stream and finally the jet material completely jams shores cracks. It is the welding of the crack and healing of the micro-defects which takes place.

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1. Introduction

The energy or electromagnetic field has long been used for material processing by pressing methods. Induction or contact heating (due to the dissipation of electromagnetic energy) of a workpiece by electric current of low density and $j \approx 10^6 \text{ A/m}^2$ long exposure time $\tau \approx 10^3 \text{ s}$ is, similar to annealing, a thoroughly studied technology for processing of metals and alloys. Such exposure leads to homogeneous (integrative) heating of the material volume to a temperature comparable to the melting point (as a general rule $T \geq 0,6T_{\text{melt}}$), and, as a result, to a decrease in the absolute values of the material mechanical properties, including its yield strength. This facilitates machining of the heated workpiece. If one should make the impact of electromagnetic field on conductive material intensive and short-term by the exposure of such material to pulsed current density $j \approx 10^9 \text{ A/m}^2$ and for time $\tau \approx 10^{-4} \text{ s}$, the workpiece surface temperature after the exposure will not rise higher than several dozens degrees (depending on the exposure parameters and the material properties). In addition, this exposure does not seriously change the material elasticity (in contrast to the integrative heating), while its plasticity improves a lot, namely, the yield strength decreases and plastic deformation before fracture significantly increases (from several dozens to a hundred per cents for different materials and alloys [1-5, 7-9, 11]). In this case, the material reserves the improved plasticity for the whole period after the exposure to the current, but not only during or immediately after the current impact (when the workpiece is hot). This makes it possible to use the effect in production, both together with mechanical treatment and when alternating electrical and mechanical treatments. This phenomenon was called *electroplastic effect*. The principal difference of this effect from the integrative heating (and from the annealing) lays in the mechanisms of electromagnetic field impact causing the increase of the ultimate plastic deformation. These mechanisms are different from the ones of the integrative heating [1-6, 10-11, 14, 20-26].

The effect is widely used in production, especially when processing such hardly deformed materials as: high-strength steels, alloys based on titanium, tungsten, magnesium, conductive composites, ceramics, etc.

Despite its wide use in production, a uniform opinion on the nature of such effect has not been formed yet, and the discussion of its fundamental principles and physical mechanism is still open [1-11, 14, 20-27].

Skipping details of the hypotheses that refer to the solid-state physics as applied to single-crystalline metals in order to explain the electroplastic effect [1-2, 5, 10-11], a note should be made about the inability of these hypotheses to explain high material plasticity observed after the removal of the electromagnetic field. In addition, the hypotheses do not coincide with other experimental data [3-4, 21-22]. Apart from this, application of such models to

polycrystalline metals (that compose the great majority of parts and structural elements) raise some questions, in particular it is debatable whether the plasticity mechanism in these metals is limited within dislocation kinetics, vice versa, it is largely attributable to mutual grain dislocation and turning, moreover the fracture at plastic deformation occurs due to appearance and increase of the defects at the grain boundaries [25].

A hypothesis about material defect healing (change) under the electromagnetic field [3-4, 20-27] is one of the explanations of the electroplastic effect. In the mentioned papers, the healing meant both appearance of compressive stresses at the tips of the cracks and closing-in movement of the cracks edges accompanied by craters (pores) fusion at the tips of the cracks, which prevented further growth of the cracks in the material.

Polycrystalline metals may have the following defects: intergrain microdefects formed by the surfaces of neighboring grains (single crystals), as well as meso and macrodefects. The latter are most often formed when the material is deformed in the process of its machining. In contrast, microdefects having linear sizes from a few microns to $50 \mu\text{m}$ can initially be present in undeformed material, as a result of casting for example. Flat microcracks are the most dangerous of the microdefects in terms of fracture.

The defects in the material cause localization (concentration) of the electric field in their vicinity. This leads to locally inhomogeneous temperature distribution throughout the material due to increased dissipation of electromagnetic energy in the defects area, mainly at their sharp tips.

It has been noticed long ago that inhomogeneity in an unbounded conductive medium leads to concentration of the electric field in its vicinity [15]. The paper provides the solution of how to determine the electrostatic field around a conductive ellipsoid in an external homogeneous field (here, it is necessary to consider formal analogy of the equations of electrostatic field in dielectrics and stationary current distribution in an unbounded conductive medium). However, it was as late as in [12] when this fact was used to explain the retardation, achieved by means of short current pulses, of a high density of cracks propagating in siliceous iron. Furthermore, the experiments showed temperature leap in the vicinity of the tips of macrocracks in ferrous and non-ferrous metals that was accompanied by material melting, evaporation and creation of a crater caused by micro-explosion when exposed to current [12-13].

The elastic problem of an impact on a disk-shaped crack (mathematical section) in an unbounded conductive medium by a homogeneous distant current field perpendicular to its plane (assuming the applied current density is small and the temperature field perturbation described by the equation of stationary heat conduction is stationary) has been being solved analytically in [16-17]. As a result, the current on the contour of the crack increased without bound, the vicinity warmed up. The temperature in

the crack centre was lowered (about 2 times lower than in its contour region). This caused crack-opening tensile stresses in the crack center. However, [16] makes an assumption about the possibility of the opposite effect: high current density and a non-stationary heat conductivity can generate the temperature at the crack tip sufficient to close and heal the crack.

The problems of the impact on instantly formed semi-infinite and finite cracks (in the form of mathematical sections) in an unbounded conductive elastic plate by a short current pulse perpendicular to its plane were solved analytically with a number of simplifying assumptions respectively in [18-19]. The temperature field was described by a non-stationary heat conductivity equation with instantaneous point sources in the tips of the cracks. At the tips, the current density increased without bound, the temperature raised, and the tips' normal temperature stresses became compressive and prevented the development of the cracks. However, melting in the tip of the crack began only at $j \approx 2 \cdot 10^{10} \text{ A/m}^2$ and $\tau \approx 3 \cdot 10^{-3} \text{ s}$, which did not correspond to the experimental data [12-13]. On the contrary, the heating rate and temperature gradients in the vicinity of a crack tip, obtained from a model, turned out to be significantly less than those observed in these experiments.

In [20-22], the problems of the impact on a crack (mathematical section) in unbounded conductive elastic medium by a current perpendicular to its plane (plane strain-deformation) were solved analytically. As in [16-19], it was supposed that the current effect on the material is only associated with the release of Joule heat. The solution was sought under the assumption that the effect of a short current pulse can be simulated by instantaneous point heat sources placed at the tips of a crack (the temperature field was described by a non-stationary heat conductivity equation). The calculated equivalent stress factor turned out to be negative, which indicated the presence of compressive stresses in the tips of the cracks, normal to the crack plane. In addition, [20-22] provide a fundamental analytical study of residual stresses in unbounded rigid-plastic medium when such stresses resulted from various heat sources simulating the effect of a defect on the stress-strain state in material.

[23-24, 26] propose a quasi-stationary model of electrothermoplastic deformation of material and a step-by-step numerical method for solving the resulting system of equations (the solution of the thermomechanical problem was built on the basis of the solution of the electrothermal one). There was solved the plane problems of deformation of representative elements and material samples containing, respectively, single mesodefects and macrodefects (in the form of flat cracks with rounded tops and circular pores) and their ordered set under various modes of electrodynamic and thermo-mechanical loads. It was shown that near macrocracks and macropores, inhomogeneous temperature field appeared with localized temperature that

reached the melting point in the vicinity of the macrocracks tips (no melting was observed at the macropores ends). The compressive stresses in the vicinity of cracks led not only to the crack development retardation, but also to closing-in movement of the crack edges (partial closure of the defect). Despite this, this model, like the models in [18-22], only allowed to describe qualitatively the heating and deformation process: heating rate, temperature gradients, time when the melting in the vicinity of a crack tip starts, obtained from the model, did not correspond to those observed in experiment [12-13].

In the mentioned [16-24, 26], the stress-strain state caused by current was considered quasi-stationary, moreover, the Fourier thermal conductivity law was assumed valid. Both these assumptions were omitted in [27], which offered a dynamic model of electrothermoplastic deformation and a step-by-step numerical method for solving the resulting system of equations in order to study fast processes occurring at the level of microdefects under short exposure times (10^{-5} - 10^{-4} s) of the material to electromagnetic field with regard to the material phase transformations (melting and evaporation). It showed large gradients of the electromagnetic field and current density in the vicinity of microcracks with rounded tips. This leads to intense heating, melting and evaporation of the metal in their tips. Under the appearing thermal stress, the molten material tends to leak into the crack. Similar to quasi-statics in the non-stationary wave formulation, the microcracks edges also demonstrated closing-in movement. These processes were consistent with those observed in experiments [12-14] and led to retardation of the microcracks propagation.

Due to mathematical difficulties in analytical solution of electrothermoelastic and numerical solution of electrothermoelastoplastic (with finite deformations) problems, none of the models [16-24, 26-27] allowed us to consistently track the effects of the stress-strain state in the vicinity of a defect on the electric and temperature fields and to complementary explore the entire process of the defects evolution under the influence of a current pulse. In addition, none of these models (with the exception of [27]) took into account the dependence of metal physical and mechanical properties on temperature, and changes in aggregation state of the substance in the deformation process. Meanwhile, as shown in [3-4, 12-13], the absolute temperatures obtained in the experiments are very high, they certainly exceed the melting point and reach the metal evaporation temperature. Under such conditions, it is impossible not to take into account the dependence of metal properties on temperature, as well as changes in the substance aggregation state.

To eliminate these drawbacks, this paper proposes a quasi-stationary model of high-energy short-pulse electromagnetic field impact on microcracks in metal, and a numerical method for solving the resulting system of equations. The constructed model was used to solve the problem of a short-term impact of electric current on flat

microcracks with rounded tips. In addition, the paper contains a study of changes in the electromagnetic and temperature fields, aggregate and stress-strain states in the vicinity of microcracks. The study of these processes will allow to have an insight on the mechanism of the electroplastic effect in the context of the defects healing hypothesis and to come closer to explaining the experimentally observed changes in the plastic properties of metals.

2. Objectives and Main Model Equations

The material considered was conductive and with an ordered defect structure. It consisted of periodically distributed representative elements, as shown in Figure 1 (right) that had the defects such as flat microcracks with rounded tips. The material was exposed to short-term pulsed high-energy electromagnetic field of a particular intensity (current density from 10^8 to 10^{10} A/m² and duration of 10^{-5} - 10^{-4} s). The solution is sought for the material representative element shown in Fig. 1, *a*.

In doing so the objective is to investigate the processes of change in the electric and temperature fields in the material and their influence on phase transformations and stress-strain state in the vicinity of microdefects.

A quasi-stationary model of electromagnetic field impact on pre-damaged defective material is proposed to get this objective. The solution of the resulting system of equations is sought by the finite element method.

To obtain electric potential in a conductive material, the charge conservation law is used under the assumption that the current in the sample is steady, as well as Ohm's law [15]:

$$\int_S \mathbf{j} \cdot \mathbf{n} dS = \int_V r_c dV, \quad (1)$$

$$\mathbf{j} = \sigma^E(T) \mathbf{E} = -\sigma^E(T) \frac{\partial \varphi}{\partial \mathbf{x}}, \quad (2)$$

where V is an arbitrary volume bounded by a piecewise smooth surface S ; $\mathbf{n}$ is the outward normal to S ; $\mathbf{j}$ is the current density and r_c is the internal volume current source per a unit of volume, $\mathbf{E}(x)$ is the intensity of the electric

field, defined as the negative gradient of the electric potential $\mathbf{E} = -\partial\varphi/\partial x$, φ is the electric potential, $\sigma^E(T)$ is the conductivity matrix, T is the temperature.

From (1), using the Gauss-Ostrogradsky theorem and the arbitrariness of the volume V , we obtain the corresponding differential equation, which can be written in the weak Bubnov-Galerkin form. Then, integrating the latter in parts and using (2), we obtain the basic equation of the finite element model for the electric potential:

$$\int_V \frac{\partial \delta \varphi}{\partial \mathbf{x}} \sigma^E \frac{\partial \varphi}{\partial \mathbf{x}} dV = \int_S \delta \varphi j dS + \int_V \delta \varphi r_c dV, \quad (3)$$

where $j = -\mathbf{j} \cdot \mathbf{n}$ is the current density normal to the surface S , $\delta \varphi$ is variations of the electric potential satisfying the boundary conditions of the problem. In the following calculations, we assume $r_c = 0$.

The displacement field $\mathbf{u}$ is determined from the principle of virtual work [28]:

$$\int_V \boldsymbol{\sigma} : \delta \boldsymbol{\varepsilon} dV = \int_S \mathbf{t} \cdot \delta \mathbf{u} dS + \int_V \mathbf{f} \cdot \delta \mathbf{u} dV, \quad (4)$$

where $\boldsymbol{\sigma}$ is the stress tensor, $\boldsymbol{\varepsilon}$ is the total deformation tensor, $\mathbf{f}$ is the vector of volume forces, $\mathbf{t}$ is the vector of surface forces, $\delta \mathbf{u}$ and $\delta \boldsymbol{\varepsilon}$ is the variation of displacements and the corresponding total deformations.

The displacements are assumed to be finite. The additivity of the speeds of elastic $\dot{\boldsymbol{\varepsilon}}^{el}$, plastic $\dot{\boldsymbol{\varepsilon}}^{pl}$ and temperature $\dot{\boldsymbol{\varepsilon}}^{th}$ deformations is accepted as follows:

$$\dot{\boldsymbol{\varepsilon}} = \dot{\boldsymbol{\varepsilon}}^{el} + \dot{\boldsymbol{\varepsilon}}^{pl} + \dot{\boldsymbol{\varepsilon}}^{th}. \quad (5)$$

Equation (5) is valid under the assumption that the elastic and temperature deformations are small [31-33] (while plastic deformations are finite). This assumption shows good accuracy for metals and their alloys. In this case, the elastic response of the material can be considered linear without the accuracy loss. The Hooke's law for an isotropic body and the associated law of flow with the Mises plasticity condition are assumed correct for the speeds of elastic and plastic deformations.

Fig. 1. The representative element: *a* is the arrows show the direction of current density vector at the boundary, the ordered structure of defects (*b*) and the finite element mesh in the integration region for a horizontal microcrack (*c*)

$$\dot{\boldsymbol{\sigma}} = \lambda(T) \dot{\boldsymbol{\varepsilon}}^{el} : \mathbf{I} + 2\mu(T) \dot{\boldsymbol{\varepsilon}}^{el},$$

$$\dot{\boldsymbol{\varepsilon}}^{pl} = \dot{\Lambda} \frac{\partial \Phi}{\partial \boldsymbol{\sigma}} = \dot{\Lambda} \mathbf{s}, \quad \bar{\boldsymbol{\sigma}} = \boldsymbol{\sigma}_Y(T), \quad \bar{\boldsymbol{\sigma}} = \sqrt{\frac{3}{2} \mathbf{s} : \mathbf{s}}, \quad (6)$$

where $\lambda(T)$, $\mu(T)$ are Lamé elastic modules, $\boldsymbol{\sigma}_Y(T)$ - is yield strength, $\mathbf{s}$ is a stress deviator, $\mathbf{I}$ is a unit tensor. Temperature deformation in differential form is taken in the following form:

$$d\boldsymbol{\varepsilon}^{th} = \alpha(T) \mathbf{I} dT \quad (7)$$

where $\alpha(T)$ is thermal expansion coefficient.

Energy conservation law was used to obtain the temperature field [29]:

$$\int_V \rho \dot{U} dV = \int_S q dS + \int_V r dV, \quad (8)$$

where ρ is density, $\dot{U}$ - material derivative of internal energy, q - heat flux per a unit of area normally to the surface S and r - power density of volume heat sources.

Since the time of electromagnetic impact on the material is 10^{-5} - 10^{-4} c, conductivity should be neglected and the process should be considered adiabatic. The attention should be paid to the following experimental data. According to experiments [12-13], temperature gradients measured in the vicinity of a crack when exposed to short current pulses are very large, exceeding 10^7 °C/m. At such values of $\text{grad}T$, the Fourier thermal conductivity law is not satisfied [34-35]. In addition, [36-37] showed for various metals good agreement between the increase in temperature measured in experiments at different places of samples under the a current pulse and calculated as a result of Joule heat released under adiabaticity conditions. In this connection, applying the Gauss-Ostrogradsky theorem to equation (8), we obtain temperature evolution equation:

$$\rho(T) c(T) \dot{T} = r^E + r^{pl} + r^{melt} + r^{evap}, \quad (9)$$

where c is specific heat capacity, $\dot{T}$ - material derivative of temperature, r^k - heat released in a volume unit in the current body configuration per a unit of time $k = E, pl, melt, evap$, where r^E - heat released by electric current flow, r^{pl} - heat released during plastic deformation, r^{melt} - heat, absorbed in the melting process, r^{evap} - heat, absorbed in the evaporation process.

Thermal energy per a volume unit in the current body configuration per a unit of time, released due to dissipation of electromagnetic energy when the current flows in a conductor, is determined by Joule-Lenz law and is taken in the form:

$$r^E = \eta^E \mathbf{j} \cdot \mathbf{E} = \eta^E \nabla \varphi \cdot \boldsymbol{\sigma}^E \cdot \nabla \varphi, \quad (10)$$

where η^{pl} is an empirical coefficient that has dissipated into heat. The coefficient is defined as the fraction power of the electric current per a volume unit. This coefficient is

assumed to be constant in the model (in the above calculations $\eta^E = 1$ [38]).

Due to plastic deformation under adiabatic conditions, most plastic work is dissipated into heat. The model assumes that the plastic deformation leads to heat release in the a volume unit of the body per a unit of time:

$$r^{pl} = \eta^{pl} \boldsymbol{\sigma} : \dot{\boldsymbol{\varepsilon}}^{pl}, \quad (11)$$

where η^{pl} is an empirical coefficient that has dissipated into heat. The coefficient is defined as the plastic fraction power of the current per a volume unit. This coefficient is assumed to be constant in the model ($\eta^{pl} = 0,9$ [39]).

As it has been mentioned in the introduction, the temperature in these processes varies from the room temperature to the temperature of metal evaporation. In this situation, it is impossible not to take into account the dependence of metal properties on temperature. For this reason, in the proposed model all physical and mechanical properties of material (density, specific heat capacity, electrical conductivity, thermal expansion coefficient, elastic moduli, yield strength, etc.) included in the above equations depend on temperature.

The areas of phase transformations (melting and evaporation of the material) were determined as follows:

The material was assumed to melt at time t_s when it reaches the temperature at the point $T \geq T_{melt}$, where T_{melt} is the material melting point. From this moment on, there simultaneously were two phases at this point (medium volume) (solid and liquid) [30]. This continues until this medium volume at time t_1 receives the amount of heat $\rho \Lambda_{melt} dV$, where Λ_{melt} is latent heat of melting. At this time t_1 , the solid phase becomes completely liquid. The temperature in this medium point remains constant for the following period $t_s \leq t \leq t_1$:

$$T = T_{melt}, \quad t_s \leq t \leq t_1. \quad (12)$$

Time t_1 , when the material becomes completely melted is defined as:

$$\int_{t_s}^{t_1} (r^E + r^{pl}) dt = \rho \Lambda_{melt}. \quad (13)$$

At the points where the material had melted, there was a sharp change in all physical properties of the material: electrical conductivity, heat capacity, density, coefficient of linear expansion and all other mechanical properties of the material. Such change in the material properties corresponds to the available experimental data [40-42]. Fig. 2 shows the change in some of these properties caused by temperature for zinc.

Thus, within the proposed model, when the melting temperature is reached, the material does not lose the ability to conduct electric current (Fig. 2, a) and the melt keeps being heated. The elastic moduli, yield strength (Fig. 2, b, c), and the coefficient of thermal expansion decrease. The further behavior of the material is described by the governing equations (5)-(7).

Fig. 2. Dependences (a) of electrical conductivity σ^E , (b) of Young's modulus E , (c) of yield strength σ_y on temperature T (vertical dashed lines indicate melting point – $T_{melt} = 419$ °C and evaporation temperature – $T_{evap} = 906$ °C)

The material was assumed to evaporate at time t_s when it reaches the temperature at the point $T \geq T_{evap}$, where T_{evap} is the material evaporation temperature. From this moment on, there simultaneously were two phases at that point (medium volume) (solid and liquid). Like in case of melting, the temperature in this medium point remains constant for the following period $t_{el} \leq t \leq t_{ev}$:

$$T = T_{evap}, \quad t_{el} \leq t \leq t_{ev}. \quad (14)$$

Time t_{ev} when the material becomes completely evaporated (the liquid phase at a medium point completely transforms to the gaseous one) is determined by the equation:

$$\int_{t_{el}}^{t_{ev}} (r_e + r_{pl}) dt = \rho \Lambda_{evap}, \quad (15)$$

where Λ_{evap} is latent heat of evaporation. At the points where the material has completely evaporated, at all subsequent times, it was assumed: current density $j = 0$, stress tensor $\sigma = 0$, temperature of a constant $T = T_{evap}$.

Thus, within the proposed model, when the evaporation temperature is reached, the material loses the ability to conduct electric current and its heating stops. The speed of metal evaporation in a crack is believed to be equal to the one in vacuum equal, that is the speed of sound. Herewith, the metal loses its properties of viscous fluid and is considered to be rarefied gas.

By virtue of symmetry, the integration region was set equal to a half of the representative volume (for horizontal microcracks) with boundary conditions for plane deformation:

$$j_y(x, b) = j_0, \quad j_y(x, -b) = j_0, \quad j_x(x, b) = j_x(x, -b) = 0,$$

$$\partial \varphi / \partial x|_{x=0} = \partial \kappa / \partial x|_{x=a} = 0, \quad (16)$$

$$x = 0: \quad u_x = 0, \quad \sigma_{xy} = 0, \quad y = \pm b: \quad u_y = 0, \quad \sigma_{xy} = 0. \quad (17)$$

$$x = a: \quad u_x = 0, \quad \sigma_{xy} = 0 \text{ or } x = a: \quad \sigma_{xx} = 0, \quad \sigma_{xy} = 0. \quad (18)$$

The crack did not conduct current, therefore the normal derivative of the potential at its boundary was set equal to zero. Crack surface assumed to be free of stress. The initial fields of temperature, displacements, and electric potential were assumed to be homogeneous ($T_0 = 20$ °C, $u_0 = 0$, $\varphi_0 = 0$).

Equations (2)-(7) and (9)-(15) form a complete system of equations for an electrothermomechanical problem. All system equations are connected and numerically solved together (in contrast to the models in [23-24, 26-27], where the solution of thermomechanical problem was sought on basis of the solution of thermoelectric one). The temperature T is not a degree of the problem freedom; it is calculated from equations (9)-(15), which are solved directly at each integration point using the approximation of the derivative of temperature by the inverse time difference. Coupled nonlinear system of equations (2)-(7) together with the boundary conditions form a boundary value problem, which is solved by the finite element method with respect to the displacement vector u and the electric potential at each time step. The calculations were performed for plane deformation using linear four-node isoparametric finite elements. The grid restructured on the basis of mixed Euler-Lagrangian method.

3. Numerical Simulation Results

The calculations were performed with the use of ASTRA computational package developed under the guidance of prof. N.G. Burago in Solids Mechanics Simulation Laboratory of Ishlinsky Institute for Problems in Mechanics RAS.

The current density at the boundary of the representative element was constant during the entire time of exposure to electromagnetic pulse τ_0 . For all microcracks, the initial distance between the edges was set as 1 μm , and the curvature radius – 0.5 μm . Representative element dimensions: $a = 120 \mu\text{m}$, $b = 80 \mu\text{m}$. The simulation was performed for zinc samples.

Calculations of the proposed model show that when electric current flows through the defected sample (Fig. 1), there are large electric field gradients in the vicinity of flat cracks. These gradients lead to a significant increase of the current density in the vicinity of the cracks tips compared to the current density applied to the sample. Away from the defect at distances approximately equal to the microcrack length, the field of current density is weakly perturbed (the current density is close to the density of the applied current, as in the sample without defects). Such processes as heating, phase transitions and deformation in the vicinity of defects depend on the concentration (localization) of the electromagnetic field. Absolute value of the maximum current density can be chosen as an indicator of the field concentration.

Fig. 3, *a* shows the dependence of maximum current density j in the tip of a flat microcrack on its length l_0 (at a constant number of defects in the sample). Fig. 3, *b* shows the dependence of maximum current density j (A/mm^2) in the upper tip of a flat microcrack of 50 μm on the angle of the crack plane inclination to x -axis. The calculations were performed under the current pulse of $1.5 \cdot 10^2 \text{ A/mm}^2$.

The provided graphs demonstrate that the increase of a microcrack size by an order of magnitude leads to a decrease of the maximum current density at its tip by only 2.8 times; and also that the maximum current density at the tip of a crack remains almost constant in the angular range of 0-15, its further decrease at an increased angle is insignificant (does not exceed 25 %). The considered range of lengths and angles of microcracks covers all the most probable lengths and angles of defect formation in the case of preliminary plastic deformation of the metal before the material is treated with current (we assume that this deformation occurs in the direction of the current flow along the y -axis).

In addition, the simulation revealed that there are regions on microcrack edges in their central part (at a distance of a half of the crack length from its tip), where the current density is only a few A/mm^2 , that is, 100 times less than the density of the applied current. While the current density in microcrack tips can exceed the density of the applied current by an order of magnitude (Fig. 3).

Fig. 3. Dependence of maximum current density on the microcrack length (*a*), inclination (*b*)

In view of the foregoing, from this point on, when considering the current impact on microcracks, we limit ourselves to considering horizontal cracks ($\alpha = 0^\circ$) with a size of 10 μm , and we will assume that for microcracks of 10-50 μm with inclination angles of 0-30° the considered processes will qualitatively occur in a similar way.

Fig. 4 respectively shows (a) current density fields and (b) temperatures (at time $t = 24.5 \mu\text{s}$) in the vicinity of the tip of a microcrack with a length of 10 μm when exposed to a current pulse of $7.3 \cdot 10^3 \text{ A/mm}^2$ for 50 μs . The right boundary of the integration region was conditioned by the location of the microcrack inside the sample in a surrounding of similar microcracks-condition 1 (18) (see Fig. 1). The dashed line in the figures shows the initial boundary of the crack (at $t = 0$).

The impact resulted in high values of current density with large field gradients appeared in the vicinity of microdefects. This causes rapid non-homogeneous local heating in the vicinity of a microcrack tip and the material melting accompanied by its thermal expansion (at the same time, central part of the crack edges is not heated). This leads to large compressive stresses (the pressure was over 100 MPa) in the vicinity of a microcrack and, as a result, closure of its edges, shortening of its length and release of molten material into the crack.

The closure of the edges, shortening of the length and release of molten material into the crack start almost simultaneously but not immediately after the exposure to

current: heating of the crack tips area to a sufficient temperature and the start of the melting requires some time (approximately 19 μs). An expanding jet of metal, only part of which is melted, is clearly visible in Figure 4b. This is due to the fact that the compressive stresses are so great that the material does not have time to get heated up to the melting point and plastically flows from the zone of maximum concentration of current density. In this case, the maximum current density is observed not at the point of the initial tip of the crack, but around new concentrators (see Fig. 4, a).

Distribution of electric current density, A/mm^2 (1 - 500, 2 - 1500, 3 - 3000, 4 - 6000, 5 - 9000, 6 - 15000, 7 - 21000, 8 - 27000, 9 - 30000)

Distribution of temperature, $^{\circ}\text{C}$ (1 - 50, 2 - 100, 3 - 200, 4 - 300, 5 - 350, 6 - 400, 7 - 419)

Fig. 4. Isolines (a) of current density A/mm^2 and (b) of temperature $^{\circ}\text{C}$ at $t = 24.5 \mu\text{s}$ in the vicinity of the microcrack, initial temperature was 20°C , applied current – 7.3 kA/mm^2

The process of simultaneous cracks reduction and metal ejection leads to the contact of cracks edges with the material jet. In these places, the current begins to flow, and the temperature rises (solid horizontal black lines in the region of the crack tip in Fig. 4). This process continues until the jet is completely clamped by the crack edges (Fig. 5) at the time $t = 26.4 \mu\text{s}$. Over a few microseconds (about 8 μs), the crack length shortens from 10 μm to 2.68 μm and its width reduces from 1 μm to 0.11 μm . Thus, central part of the crack edges becomes “welded” by the molten metal. The average microcrack “welding speed” at this stage is approximately 0.92 m/s. Further, the entire process above is repeated again for the microcrack of new smaller sizes. This leads to complete healing of the microcrack.

The described deformation process is accompanied by very intense plastic deformation in the vicinity of a microcrack. Fig. 5 shows the intensity of plastic deformation (the second invariant of the plastic strain tensor) at time $t = 26.4 \mu\text{s}$ (after the complete jet “clamping”). Viscous fracture of the material and the formation of a new discontinuity (defect) at the place of a healed microcrack should not occur since plastic deformation happens under the conditions of strong all-round compression.

Fig. 5. Crack boundaries and isolines of plastic deformation intensity at time $t = 26.4 \mu\text{s}$ (1 - 0.01, 2 - 0.0375, 3 - 0.065, 4 - 0.0925, 5 - 0.12, 6 - 1.00)

Fig. 6 shows temperature field (at time $t = 104.5 \mu\text{s}$) in the vicinity of the tip of a microcrack with a length of 10 μm when exposed to a current pulse of $7.3 \cdot 10^3 \text{ A/mm}^2$ for 50 μs . The right boundary of the integration region was conditioned by the location of a microdefect close to sample surface in the simulation – condition 2 (18). In this case, the compressive stresses are not as great as for a crack surrounded by similar microcracks and located inside the sample (Fig. 1). Therefore, the release of molten material and the reduction of crack size occur with a delay. During this time, the material in the tip of the crack gets very hot. This leads not only to its melting, but also to metal evaporation. Fig. 7 respectively presents the dependences of maximum current density j (A/mm^2) and temperature T ($^{\circ}\text{C}$) at the microcrack tip at time t (μs). The graphs demonstrate that the maximum current density at the crack tip decreases with the increased temperature and at time $t = 27.5 \mu\text{s}$ the temperature reaches $T_{\text{melt}} = 419^{\circ}\text{C}$. After that the material begins to melt (the plateau on the graph) accompanied by constant current density. Further drop in current density and rise of temperature slow down, but at $t = 95 \mu\text{s}$, the temperature at the microcrack tip reaches a critical value ($T_{\text{evap}} = 906^{\circ}\text{C}$) starting intensive evaporation with vapor transfer into the defect. Zones where the material has evaporated are marked with red in Fig. 6.

The calculations results of the proposed model were compared with existing experiments [12-13], in which a sharp increase of temperature was observed at a crack tip in a thin plate when exposed to short current pulses of high density: Measured heating speed was 10^7°C/s ,

temperature gradients were $6.0 \cdot 10^6 - 5.0 \cdot 10^7$ °C/m, and the temperature away from the crack did not exceed 10 °C. The tip of the crack was observed to have the material melting, evaporation, accompanied by a microexplosion, product release from the crack tip in the direction perpendicular to the plate plane, and formation of a crater. The numerical results obtained using the proposed model for zinc are in good agreement with the experiment: calculated (in the vicinity of the tip of a crack with a radius of 5 μm) average heating speed reached $6.3 \cdot 10^7$ °C/s, temperature gradients - $10^7 - 10^8$ C/m. Away from the crack the temperature did not exceed 10 C (at 100 μs), the crack edges away from the tip also were not getting hot. The process was accompanied by melting at the tip of the crack with the “ejection” of a jet of molten material in the direction perpendicular to the plate plane, as well as by evaporation of the metal.

Fig. 6. Temperature isolines at time $t = 104.5 \mu s$ (1 - 30 °C, 2 - 50 °C, 3 - 100 °C, 4 - 200 °C, 5 - 300 °C, 6 - 419 °C, 7 - 906 °C), 6 - melting zone, 7 - evaporation zone, initial temperature 20 °C, applied current 7.3 kA/mm²

Fig. 7. The dependence of the maximum current density j , kA/mm² (solid line) and temperature T , °C (dashed line) at the crack tip on time in microseconds (horizontal dashed lines indicate the melting point - $T_{melt} = 419$ °C and evaporation temperature - $T_{evap} = 906$ °C)

The effect of reducing (healing) microdefects in the material, resulted from the numerical simulation, is consistent with the one observed in experiments [14]. Figure 8 shows the microstructure of titanium alloy samples through an optical microscope [14]. Samples were tested for uniaxial stretching at room temperature (a) without exposure to current and (b) with simultaneous deformation and exposure to a pulse of current density of 5.26 kA/mm²

for 110 μs. Stretching and exposure to current were carried out in the same direction (along y -axis, Fig. 1).

Fig. 8. The material microstructure observed through an optical microscope when stretching the sample (a) at no exposure to current and (b) at simultaneous exposure of the sample to current of 5.26 kA/mm²

Thus, there is a reason to believe that the model correctly reproduces the main features of electrothermomechanical processes in the vicinity of microdefects.

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