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Healing of cracks in plates by strong electromagnetic field

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Abstract

The problem of a pulsed high-energy electromagnetic field action on an edge crack in a thin plate, reproducing the pioneering experiment of Soviet scientists on the destruction of the crack tip by a strong electromagnetic field, is considered. The numerical simulation is based on the proposed electrothermomechanical model of a short-pulse high-energy electromagnetic field (HEMF) action on a material with a crack. The model takes the phase transformations (melting and evaporation) of the material occurring in the vicinity of defects and the corresponding changes in the rheology of the material in the areas of these transformations into account, as well as the possibility of electric current flowing between the free surfaces of the crack (breakdown due to electron emission). All physical and mechanical properties of the material are considered temperature-dependent. The model equations are coupled and solved together on a moving finite element grid using the arbitrary Euler–Lagrangian method. The processes of localization of the current density and temperature fields, phase transformations (melting and evaporation) at the crack tip, autoelectronic and thermoelectronic emissions between free crack surfaces, and the effect of these processes on crack healing are investigated. The simulation results are compared with the available experimental data on the pulse field action on the edge crack in the plate. The average metal heating rate, temperature gradients and time forming of the crater obtained in the vicinity of the crack tip are in good quantitative agreement with the experimental data. Away from the crack, as well as on the crack sides away from the tip, the temperature rises slightly. The process of modeling the electromagnetic field action, similar to the experiment,

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Review Article

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was accompanied by melting at the crack tip, as well as metal evaporation. Thus, under the considered current action, a crater is formed at the crack tip, which prevents the further spread of the crack, leading to its healing. It was not possible to obtain similar results using the previously proposed models.

Keywords: pulsed electromagnetic action, defect healing, crack arrest, high-energy field.

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Introduction. An external electromagnetic field is applied to the conductive sample, which induces a current in the material with a current density of 10^8 to 10^{11} A/m^2 during short time interval. A pulsed electromagnetic field is called a high-energy electromagnetic field (HEMF) if electromagnetic action during $10^{-4} - 10^{-3}$ s leads to amount of the scattering specific electromagnetic energy in the material within the range $10^8 \leqslant q \leqslant 10^{10}$ J/m^3.

The presence of defects in the conductive solid leads to the localization (concentration) of the electric field in their vicinity. This causes a locally inhomogeneous temperature distribution in the material, due to the increased dissipation of electromagnetic energy in the area of defects, or rather in their sharp tips. The use of this circumstance to explain the healing by short pulses of high-density current of cracks propagating in siliceous iron under the influence of pulsed HEMF was carried out for the first time in [1].

Experiments [1, 2] show that HEMF action leads to a sharp temperature increase at the microcracks tips. As a result, melting, evaporation, microexplosion, and crater formation occur at the macrocracks tips.

Thus, the resulting crater prevents the further crack propagation and leads to crack healing.

In particular, these experiments showed that when short pulses of high-density current induced by the HEMF were applied to the edge crack in a thin plate in the vicinity of its tip, a sharp temperature increase was observed: the measured heating rate was 10^7 °C/s, the temperature gradients were 10^6–10^7 °C/m, and the temperature away from the crack did not exceed 10 °C. Such rates and localities of heat release led to melting and evaporation of the material at the tip of the crack, accompanied by a microexplosion, which ejected the explosion products from the crack tip in a direction perpendicular to the plate plane. At the same time, a crater formed at the crack tip [1].

A number of researchers have attempted to model the electrical, thermal, and mechanical processes that occur during the above-described pulsed action of the HEMF on a crack in a plate.

These processes were considered both in quasistatics [3–9] and in dynamics [11]. The plate material was assumed to be thermoelastic [7, 9], thermo-rigid-plastic [10], thermoelastoplastic [11], and the deformations were small. The process of thermal conductivity is described by Fourier's law. In the works [3–5], the magnetic effects arising under the HEMF pulse action were also taken into account.

The simulation showed that an inhomogeneous temperature field occurs near the macrocrack and temperature localization reaches the melting point in the vicinity of the macrocrack tip. Compressive stresses occurring in the vicinity of the crack tip led not only to the crack arrest, but also to the convergence of its sides (partial closure of the defect). However, these models allowed to describe the process of heating and deformation only qualitatively: the heating rate, temperature gradients, and the time of the beginning of melting in the vicinity of the crack tip, obtained as a result of modeling, were significantly different from those observed in experiments [1, 2]. Within the considered above models the temperature at the crack tip could not reach the evaporation temperature, therefore these models failed to describe the processes of explosion and the formation of a crater in the tip.

Due to mathematical difficulties in the analytical solution of electrothermoelastic (rigid-plastic) and numerical solution of electro-thermoelastic problems, none of the models [3–10] allowed (in the context of the assumption of small deformations) to trace the effects of the stress-strain state in the vicinity of the defect tip on the electric and temperature fields consistently. In addition, none of these models took into account the phase transformations in the metal and the resulting changes in rheology, including the dependence of the physical and mechanical properties of the metal on temperature after changes in the aggregate state of the substance during deformation. Therefore, the models under consideration did not allow coupling study of the determining processes occurring at the crack tip under the current pulse action.

Meanwhile, as shown in [1], the absolute temperature values (and its gradients) obtained in experiments are very large, they obviously exceed the melting point and reach the evaporation temperature of the metal. Under such conditions, it is necessary to take into account the changes in the aggregate state of the substance, the dependence of the properties of the metal on temperature and their influence on the stress-strain state.

To eliminate these lacks, we propose a quasi-stationary model of pulsed HEMF action on cracks in metal and a numerical method for solving the resulting system of equations.

On the basis of the developed model, the problem of the short-term HEMF action on the edge crack (with a rounded tip) in the plate is solved, which numerically reproduces the experiment performed in [1]. Changes in the electromagnetic and temperature fields, as well as in the aggregate states in the vicinity of the crack, are studied.

The study of these processes will allow us to understand the mechanism of healing of microcracks in plates under the HEMF action better and get closer to explaining the experimentally observed processes of healing fatigue cracks by welding their sides.

1. Electrothermomechanical model. Consider the dynamic response of a conducting plate to a HEMF pulse that induces a high-density electric current in the plate material for 10^{-4} s. There is an edge crack in the plate, as shown in Fig. 1. Our purpose is to reproduce the experiment carried out in the work [1] and to quantify the observed effects.

We formulate the assumptions and equations of the analytical model for describing the electrical, thermal and mechanical processes occurring in the plate

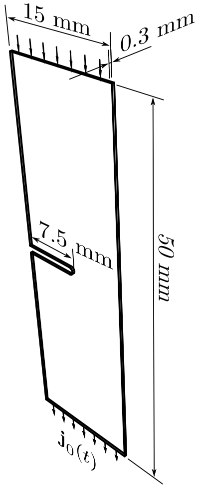


Figure 1. The sketch of the specimen 15×50×0.3 mm with the edge crack (the crack length is 7.5 mm, including the rounding at the tip with a radius of 10 µm, the crack has parallel sides and thickness is 20 µm); only the upper half of the sample is simulated in FEM due to the symmetry; $\mathbf{j}_0(t)$ are electrical current density vector applied to plate sides

material. The characteristic time of each of these processes is approximately inversely proportional to the propagation velocity of the corresponding perturbations. If we neglect the electromagnetic induction and viscosity during the propagation of mechanical disturbances, then the time required to establish the electromagnetic and mechanical processes considered in this model is 10^{-13}–10^{-12} s and 10^{-8}–10^{-7} s, respectively. This is significantly less than the time of the external action of the HEMF source (10^{-4} s).

Therefore, to obtain the electric potential φ in a conducting material, we use the law of conservation of charge (assuming that the current in the sample is steady). Since we search for a numerical solution by the finite element method, we use it in the variational formulation (1) [12]. At the same time, the laws of Ohm and Joule–Lenz are considered valid for the material.

The displacement field $\mathbf{u}$ is determined from the equilibrium equations written in the form of the virtual work principle (2) [12]. The deformations are assumed to be finite. In this case, the additivity of the rates of elastic, plastic, and temperature deformations is assumed (2). For the velocities of elastic and plastic deformations, Hooke's law for an isotropic body (3) and the associated flow law with the Mises plasticity (4) condition are assumed to be valid, respectively. The rates of temperature deformations are assumed to be linearly related to the temperature derivative (5).

The analytical estimates show that during pulsed electromagnetic field action, the current density at the crack tip is such that the relative temperature change at the distances of the order of the free path of phonons (and electrons) is greater than one. It is also evidenced by the measured temperature gradients in the vicinity of the crack vertices, which turn out to be very large [1] It is not correct to apply the Fourier law of thermal conductivity in this case. In addition, the time of electromagnetic impact on the material is small, 10^{-4} s. Therefore, thermal conductivity should be neglected and the process of HEMF exposure should be considered adiabatic (6).

The temperature field T is determined from the law of conservation of energy. In this case, we take into account the heat released in the unit volume in the current configuration of the body per unit time (6) due to the flow of electric current in accordance with the Joule–Lenz law (7), the heat released during plastic deformation (8), as well as the latent heat absorbed in the processes of melting and evaporation. Therefore, the resulting evolutionary equation for temperature should be extended with equations (9) and (10), which represent the conditions for the absorption of latent heat during the transition of a substance from one aggregate state to another: from solid to molten during melting and from liquid to gaseous during evaporation.

As noted above, during the current action on the crack in the plate, the metal temperature changed from room temperature to the evaporation temperature [1]. Therefore, all the physical and mechanical characteristics of the model (density, specific heat, electrical conductivity, coefficient of thermal expansion, elastic modulus, yield strength, etc.) are assumed to depend on the temperature over the entire range until the evaporation temperature is reached.

At the points where condition (9) is realized, the material is considered molten. In this case, there is a sharp change in all the physical properties of the material: electrical conductivity, heat capacity, density, coefficient of linear expansion and all other mechanical characteristics of the material. Such a change in the properties of the material corresponds to the available experimental data given in [14–16], which shows the dependence of the properties of various metals on temperature. In this case, there is a decrease in some (elastic modulus, yield strength, linear expansion coefficient, etc.) and an increase in others (density, etc.) of the physical characteristics of the material [15, 16].

Thus, in the model under consideration, when the melting temperature was reached the material does not lose the ability to conduct an electric current [15,16] and after the metal completely passes into the molten state, the melt is heated further. As the result, elastic modulus decreases and the yield limit falls to zero which allows us to describe the behavior of the molten material by the same constitutive equations (3)–(5), which degenerate for the melt into thermoviscoelastic with nonlinear viscosity.

At the points where condition (10) is realized the material is considered to have completely evaporated. At all subsequent times, the current density $\mathbf{j} = \mathbf{0}$, the stress tensor $\boldsymbol{\sigma} = \mathbf{0}$ and the temperature are assumed to be constant $T = T_{\text{evap}}$. Therefore, in the model under consideration, from the time when the material completely evaporates, the metal loses its ability to conduct an electric current, its further heating does not occur, it loses the properties of a viscous liquid and is considered as a rarefied gas.

The complete system of equations of the considered electrothermomechanical model has the form [12, 13]:

$$\int_V \nabla\,\delta\varphi\,\sigma^{\mathrm{E}}(T)\,\nabla\,\varphi\,dV = \int_S \delta\varphi\,j\,dS, \qquad \mathbf{j} = \sigma^{\mathrm{E}}(T)\,\mathbf{E} = -\sigma^{\mathrm{E}}(T)\frac{\partial\varphi}{\partial\mathbf{x}}, \tag{1}$$

$$\int_V \boldsymbol{\sigma}:\boldsymbol{\varepsilon}\,dV = \int_S \mathbf{t}\cdot\delta\mathbf{u}\,dS + \int_V \mathbf{f}\cdot\delta\mathbf{u}\,dV, \qquad \dot{\boldsymbol{\varepsilon}} = \dot{\boldsymbol{\varepsilon}}^{\mathrm{el}} + \dot{\boldsymbol{\varepsilon}}^{\mathrm{pl}} + \dot{\boldsymbol{\varepsilon}}^{\mathrm{th}}, \tag{2}$$

$$\dot{\boldsymbol{\sigma}} = \lambda(T)\,\dot{\boldsymbol{\varepsilon}}^{\mathrm{el}}:\mathbf{I} + 2\,\mu(T)\,\dot{\boldsymbol{\varepsilon}}^{\mathrm{el}} \tag{3}$$

$$\dot{\boldsymbol{\varepsilon}}^{\mathrm{pl}} = \dot{\Lambda}\frac{\partial\Phi}{\partial\boldsymbol{\sigma}} = \dot{\Lambda}\,\mathbf{s}, \qquad \bar{\sigma} = \sigma_{\mathrm{Y}}(T), \qquad \bar{\sigma} = \sqrt{\tfrac{3}{2}\mathbf{s}:\mathbf{s}} \tag{4}$$

$$d\boldsymbol{\varepsilon}^{\mathrm{th}} = \alpha(T)\,\mathbf{I}\,dT, \tag{5}$$

$$\rho(T)\,c(T)\,\dot{T} = r^{\mathrm{E}} + r^{\mathrm{pl}} + r^{\mathrm{melt}} + r^{\mathrm{eval}} \tag{6}$$

$$r^{\mathrm{E}} = \eta^{\mathrm{E}}\, \mathbf{j}\cdot\mathbf{E} = \eta^{\mathrm{E}}\, \nabla\varphi\cdot\sigma^{\mathrm{E}}\cdot\nabla\varphi, \tag{7}$$

$$r^{\mathrm{pl}} = \eta^{\mathrm{pl}}\, \boldsymbol{\sigma} : \dot{\boldsymbol{\varepsilon}}^{\mathrm{pl}}, \tag{8}$$

$$T = T_{\mathrm{melt}}, \qquad t_{\mathrm{sol}} \leqslant t \leqslant t_{\mathrm{liq}}, \qquad \int_{t_{\mathrm{sol}}}^{t_{\mathrm{liq}}} \big(r^{\mathrm{E}} + r^{\mathrm{pl}}\big)\,dt = \rho\,\Lambda_{\mathrm{melt}}, \tag{9}$$

$$T = T_{\mathrm{evap}}, \qquad t_{\mathrm{eliq}} \leqslant t \leqslant t_{\mathrm{evap}}, \qquad \int_{t_{\mathrm{eliq}}}^{t_{\mathrm{evap}}} \big(r^{\mathrm{E}} + r^{\mathrm{pl}}\big)\,dt = \rho\,\Lambda_{\mathrm{evap}}. \tag{10}$$

The notation in this equations is given in [12, 13].

The boundary and contact conditions for the electrical potential φ, displacements $\mathbf{u}$ and stresses $\boldsymbol{\sigma}$ at the boundaries of the integration domain used in this model, as well as the initial conditions, coincide with those considered in [12, 13].

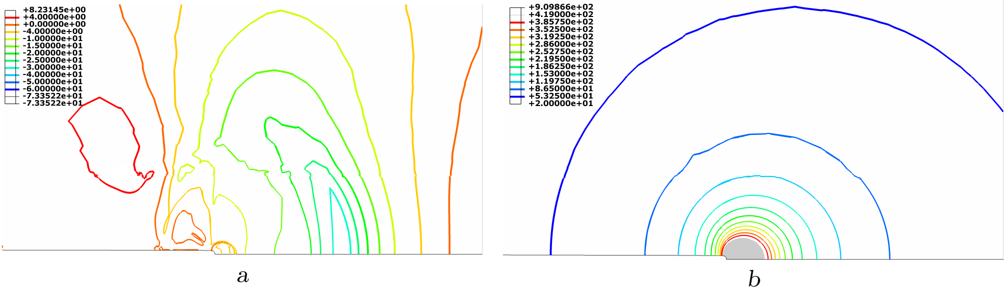
2. Results of numerical simulation. Equations (1)–(10) of the electrothermomechanical problem coupled with boundary, contact, and initial conditions were solved by the finite element method for a plate with an edge crack in a 3D formulation. The calculations were done using 20-node quadratic brick finite elements.

Simulation was done for zinc samples, the physical and mechanical properties of which and their dependence on temperature were taken in accordance with [15, 16].

The electric potential difference and its change from t used in the calculations were selected so that the induced current density coincided with the one measured in the experiment [1]. The pulse duration was 160 µs.

Fig. 2 *a* shows the stress field σ_{33} in the vicinity of the crack tip at $t = 29.5$ µs. Fig. 2 *a* shows that compressive stresses occur at the crack tip, which prevent further crack propagation. This result corresponds to the results obtained using models [3–6, 10], which also predicted the appearance of stresses compressing the crack sides at the crack tip. At the same time, calculations show that the residual plastic deformations in the vicinity of the crack tip reach tens of percent. This gives reason to believe that the restoration of the distance between the banks of the crack to the original size will not occur and after the relaxation of the temperature the sides will remain close together.

A sharp increase in temperature in the vicinity of the crack tip under HEMF pulse action was observed in the experiments presented in [1]. The measured



a *b*

Figure 2. *a*) normal stress field σ_{33} along vertical axis in the vicinity of the crack tip at $t = 29.5$ µs; *b*) temperature field in the vicinity of the crack tip at time $t = 38$ µs immediately after the forming of the crater (the gray area is the crater zone)

heating rate in the vicinity of the crack tip was on the order of $10^7\,^\circ$C/s, the local temperature gradients were $6.0 \cdot 10^6 - 5.0 \cdot 10^7\,^\circ$C/m, and the temperature change did not exceed 10 °C away from the crack. At the same time, melting and evaporation of the material was observed at the tip of the crack, accompanied by a microexplosion with the release of products from the crack tip in the direction perpendicular to the plate plane and the formation of a crater.

The results obtained by the proposed model are in good quantitative agreement with the experiment: the calculated average heating rate (in the vicinity of the crack tip with a radius of 10 µm) was $6.3 \cdot 10^7\,^\circ$C/s, and the local temperature gradients were 10^7–$10^8\,^\circ$C/m. Away from the crack, the temperature did not rise more than 10 °C (at times exceeding 100 µs), nor did heating occur on the sides of the crack away from the tip.

The process was accompanied by melting at the crack tip, as well as evaporation of the metal. Melting begins at the crack tip at time $t = 6.5$ µs, and the melt moves in a direction perpendicular to the plate plane. Evaporation begins at the time $t = 31$ µs. The time of crater formation can be associated with an interval of 31–38 µs. In the experiment, the crater was formed at 38–45 µs.

Thus, under the considered current action, a crater is formed at the crack tip, which prevents the further spread of the crack, leading to its healing.

Fig. 2 *b* shows the temperature field in the vicinity of the crack tip at time $t = 38$ µs (immediately after the forming of the crater).

Calculations based on the proposed model showed that the autoelectronic (tunnel) emission between the free surfaces (sides) of the crack does not occur due to the insufficient potential difference for this under the considered HEMF action. While the thermoelectronic emission current between the crack banks can be neglected, since its density is significantly less than the current density induced by the HEMF in the vicinity of the crack tip.

3. Conclusions. Thus, there is reason to believe that the model reproduces the main features of electrothermomechanical processes in the vicinity of microdefect correctly, describing the process of healing a crack and forming a crater.

Competing interests. We declare that we have no conflicts of interest in the authorship and publication of this article.

Authors' contributions and responsibilities. K.V. Kukudzhanov: Idea of study; Formulation of research goals and aims; Theoretical analysis; Analysis of calculation results; Supervision and consulting; Writing — original draft and review & editing. A.L. Levitin: Performing calculations, their analysis and verification; Writing — original draft and review & editing. U.Kh. Ugurchiev: Literature review; Analysis of experiments; Analysis of calculation results; Writing — part of the original draft. The authors are absolutely responsible for submitting the final manuscript in print. Each author has approved the final version of manuscript.

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Залечивание трещин в пластинах сильным электромагнитным полем

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Аннотация

Рассматривается задача о воздействии импульсным высокоэнергетическим электромагнитным полем на краевую трещину в тонкой пластине, воспроизводящая пионерский эксперимент советских ученых по разрушению вершины трещины сильным электромагнитным полем. Численное моделирование осуществляется на основе предложенной электромеханической модели воздействия короткоимпульсным высокоэнергетическим электромагнитным полем на материал с трещиной. Модель учитывает фазовые превращения (плавление и испарение) материала, происходящие в окрестности дефектов, и соответствующие изменения реологии материала в областях этих трансформаций, а также возможность протекания электрического тока между свободными поверхностями трещины (пробоя за счет эмиссии электронов). Все физико-механические характеристики материала считаются зависящими от температуры. Уравнения модели связаны и решаются совместно на подвижной конечно-элементной сетке с применением смешанного метода Эйлера–Лагранжа. Исследуются процессы локализации полей плотности тока и температуры, фазовых превращений (плавления и испарения) в вершине трещины, автоэлектронной и термоэлектронной эмиссии между свободными поверхностями трещины и влияние этих процессов на залечивание трещины. Проводится сравнение результатов моделирования с имеющимися экспериментальными данными по воздействию импульсного поля на краевую трещину в пластине. Полученные в окрестности вершины трещины средняя скорость нагрева металла и градиенты температуры неплохо количественно согласуются с экспериментальными данными.

Обзор

Образец для цитирования

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Вдали от трещины, а также на берегах трещины вдали от вершины температура поднималась незначительно. Процесс моделирования воздействия электромагнитным полем, аналогично эксперименту, сопровождается плавлением в вершине трещины, а также испарением металла. Таким образом, при рассматриваемом воздействии током в вершине трещины формируется кратер, который препятствует дальнейшему распространению трещины, приводя к ее залечиванию. Получить аналогичные результаты с помощью ранее предложенных моделей не удавалось.

Ключевые слова: импульсное электромагнитное воздействие, залечивание дефектов, торможение трещины, высокоэнергетическое поле.

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Конкурирующие интересы. Заявляем, что в отношении авторства и публикации этой статьи конфликта интересов не имеем.

Авторский вклад и ответственность. К.В. Кукуджанов — идея исследования, формулировка целей и задач исследования, теоретический анализ, анализ результатов расчетов, руководство и консультирование, черновик и чистовик рукописи. А.Л. Левитин — выполнение расчетов, анализ, визуализация и верификация результатов расчетов, черновик и чистовик рукописи. У.Х. Угурчиев — анализ литературы, анализ экспериментов, анализ результатов расчетов, черновик части рукописи. Авторы несут полную ответственность за предоставление окончательной рукописи в печать. Окончательная версия рукописи была одобрена всеми авторами.

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