Modelling of some mechanism of metal electroplasticity under pulsed high-energy electromagnetic field action

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Abstract. The processes of evolution of microcracks and micropores occurring in the material during processing of metal specimens by short-term pulses of high-energy electromagnetic field (HEEMF) are considered. The study is done numerically on the basis of a coupled model of the action an intense electromagnetic field on a previously damaged thermoelastoplastic material with an ordered system of defects, which takes into account the melting and evaporation of the metal and the dependence of all its physical and mechanical properties on temperature. Simulation has shown that, under certain conditions, microcracks can be almost completely healed. There is welding of the cracks by simultaneously decreasing the length of the microcrack, ejecting a jet of molten metal from the crack tip into the crack and closing its edges. The influence of the geometry and orientation of microdefects in the process of their healing is investigated. Based on the simulation results, simple approximate dependencies of the metal damage under the influence of the HEEMF on its initial damage, the characteristic “length” of the microdefects and their slope are obtained.

1. Introduction

Electroplasticity phenomenon is the material yield strength decrease and the ultimate plastic strain increase under a short electromagnetic pulses during or after plastic deformation. Plastic strain is accompanied by the appearance of microscopic discontinuity of the structure (microdamages or microdefects) and an increase in their number and size. Microdefects with linear dimensions of 3–10 μm are the most common defect size in the polycrystalline metals. The assumption on possibility of healing (transformation) of intergranular and intragranular microdefects in metals under the action of short pulses of a high-energy electromagnetic field (HEEMF) was done by researchers [1–5] initially to explain the phenomenon of electroplasticity of polycrystalline metals. In these works, the hypothesis of healing was supported by analytical and numerical solutions of model problems. Healing was understood as the barriers creation (due to HEEMF action) for the further cracks propagation: the occurrence of compress stresses in the tips of microcracks and the approaching of their edges, accompanied by the melting of craters (pores) in the tips. Later, in [6], on the basis of thermodynamic considerations it was shown that when we apply the current over certain threshold value, the “length” of the elliptical crack can decrease.

Since then, the hypothesis of the defects healing has received serious experimental
confirmation [7–11]. However, in these experiments not the creation of barriers to the microcracks propagation was observed, but a change of defect shape and the metals structure continuity recovery, accompanied by the microdefects volume fraction change. Thus, the experiments showed a decrease in the damage (porosity) of the material. Meanwhile, the proposed in [3–6] mathematical models did not explain damage decrease due to HEEMF action.

For a mathematical description of the physical processes taking place in the vicinity of microcracks under the action of HEEMF pulses, a model of the effect of a pulsed HEEMF on a pre-damaged material with defects was proposed [12–14]. With this model it was possible to reproduce the experimentally observed process of microdefects transformation and metal damage decrease. In [15–17] the authors showed that the shape and mutual arrangement of microdefects practically do not influence on the dependence of healing or damage of the metal on time, but depends only on the initial damage (with the same initial “length” and orientation of the microcracks).

In the present work, we consider the influence of the geometry and orientation of microcracks and micropores on changes in the healing and damage in a metal under pulsed HEEMF action.

2. Electro-thermo-mechanical model

A damaged conductive material with microdefects (microcracks or micropores) with sizes $l_0 \times h_0$ is considered. All microdefects have uniform shape, size and spatial orientation (Fig. 1). We assume that the defects in the material are arranged at the nodes of the rectangular lattice (Fig. 1b). In this case, separation of a representative cell is easy possible (Fig. 1a).

Material is under the action of a pulsed HEEMF (potential difference at top and bottom specimen boundaries) that causes the electric current in the specimen with a density $10^8 - 10^{11} \text{A/m}^2$ and duration $10^{-5} - 10^{-4} \text{s}$. The specimens sizes are much larger than microdefect size.

The solution is obtained in the integration cells shown in Fig. 1c and Fig. 1d and containing either one quarter (for $\alpha_0 = 0$) or one whole representative cell (for $\alpha_0 \neq 0$) [14–16].
The basic assumptions, equations of the electro-thermo-mechanical model, the initial, boundary, contact conditions and conditions on the interphases (solid–melt, melt–gas) boundaries are described in detail in [12,13,15,16].

In this paper we consider the parameters of the damage (porosity) \( f(t) \) and healing \( \chi(t) \):

\[
f(t) = \frac{V(t)}{V_{re}}, \quad \chi(t) = \frac{V(0) - V(t)}{V(0)}
\]

where \( V(t) \) is the volume of a single microdefect, \( V_0 = V(0) \) is the initial volume of the defect, \( V_{re} \) is the volume of the representative cell in which microdefect is located. The initial material damage at time \( t = 0 \) is \( f_0 = f(0) = V_0/V_{re} \). The volume of the microdefect under the action of the HEEMF decreases [12,13] and during pulse action the damage (porosity) will decrease, and the healing will increase.

3. Results of numerical simulation

The coupled equations of the model are solved numerically together with boundary, contact, interphase and initial conditions. The computations were performed for the plane strain using linear four-node isoparametric and three-node finite elements. The modeling was performed for zinc specimens while physical and mechanical properties of the material were dependent on temperature [18].

The representative cell sizes (\( a \) and \( b \)) varied in the range of 15–180 \( \mu m \). The influence of the shape and size of representative cells during the processes was studied in [14,15,17].

The microcracks with two parallel edges and rounded tips (Fig. 2) were considered. In the case \( h_0 = 2r_0 \) (where \( r_0 \) is the curvature radius at the crack tip) the microcrack degenerated into a circular micropore. All defects had the same initial area (in the \( xy \)-plane), but with different initial length \( l_0 \) (size along the \( x \)-axis). For all microdefects the initial damage was the same (for identical sizes of the representative cell). The initial lengths of microcracks in the calculations varied in the range 3.53 \( \mu m \leq l_0 \leq 12.5 \, \mu m \).

The slope angle of the microcrack axis was also varied in the range \( 0^\circ \leq \alpha_0 \leq 75^\circ \) (only for microcracks \( l_0 = 10 \, \mu m \)).

The potentials difference (per unit length) used in the calculations was 534.3 mV/mm in the defect–free material that corresponds to the electric current density 8.95 kA/mm\(^2\). The potentials difference was constant during pulse time \( \tau_0 = 90 \, \mu m \).

Fig. 3 shows the healed microcracks (\( l_0 = 10 \, \mu m, \alpha_0 = 0^\circ \)) and the temperature fields near it after pulse action for different initial damage. During continue HEEMF action the microcracks edges close and the molten metal jet from the crack tip clamps. Thus, the microcrack is welded.

Dependence of the damage \( f \) on pulse time \( t \), initial damage \( f_0 \), initial “length” of the microdefect \( l_0 \) and initial slope angle \( \alpha_0 \) are shown in Fig. 4.

Dependencies given in Fig. 4 are well approximated by a piecewise linear function:

\[
f(t) = \begin{cases} f_0, & t < t_0, \\ f_0 - C(t-t_0), & t \geq t_0, \end{cases}
\]
Figure 3. Microcrack healing (dashed line is the initial crack boundary at \( t = 0 \)) and the temperature contours (1 is 25\(^\circ\)C, 2 is 50\(^\circ\)C, 3 is 100\(^\circ\)C, 4 is 200\(^\circ\)C, 5 is 300\(^\circ\)C, 6 is 400\(^\circ\)C), dark gray color is melting area (\( T \geq 419\)\(^\circ\)C), black is evaporation area (\( T = 906\)\(^\circ\)C).

(a) at time \( t = 22.1 \mu s \) with initial damage \( f_0 = 0.273\% \),
(b) at time \( t = 76.6 \mu s \) at initial damage \( f_0 = 2.45\% \)

where threshold time \( t_0 = 9.63 \mu m \) and coefficient \( C = C(l_0, \alpha_0, h_0) \) is a function which does not depend on time, but depend on initial microdefect geometry and orientation.

Note that microdefects length increase leads to more slow healing (Fig. 4a), and slope angle increase leads to faster microdefects healing (Fig. 4b). This is explained by the fact that microdefects length increase leads to increase in the effective material resistivity, and current density decrease causing slower heating in the vicinity of the microdefect. Increasing the slope angle leads to the effective material resistivity decrease, and current density increase causes faster heating in the vicinity of the microdefect.

Figure 4. Dependence of the damage \( f \) on time \( t \) (\( \mu s \)) for various initial (a) microdefect lengths \( l_0 \), (b) slope angles \( \alpha_0 \) (all for initial damage \( f_0 = 2.45\% \))

Calculations also show that in the investigated range of lengths and inclinations of microcracks, the curves of damage \( f(t) \) practically coincide with each other if the projections of the initial lengths of microdefects on the \( x \)-axis are equal. Fig. 5a shows the coincidence of \( f(t) \) curves for microcracks with \( l_0 = 10 \mu m, \alpha_0 = 45^\circ \) and \( l_0 = 10 \mu m, \alpha_0 = 60^\circ \), respectively with similar curves for microdefects with \( l_0 = \frac{\sqrt{2}}{2}10 \mu m, \alpha_0 = 0^\circ \) and \( l_0 = \frac{1}{2}10 \mu m, \alpha_0 = 0^\circ \).
Therefore, it was assumed that the function $C$ in the first approximation depends only on the projection of the initial length of the microdefect on the $x$ axis: $l_{0x} = l_0 \cos \alpha_0$.

Fig. 5b shows dependence of $C(l_{0x})$ (for $t \geq t_0$). We conclude from this graph that $C$ is practically linear on $l_{0x}$ in the range $3.53 \, \mu m \leq l_0 \leq 12.5 \, \mu m$, $0^\circ \leq \alpha_0 \leq 60^\circ$ and has the form

$$C = B - A \cdot l_0 \cos \alpha_0$$

where $A$ and $B$ are defined graphical coefficients fit as

$$A = 6.95 \cdot 10^6 \mbox{ (m \cdot s)}^{-1}, \quad B = 2.01 \cdot 10^2 \mbox{ s}^{-1}$$

![Figure 5](image_url)

**Figure 5.** Dependencies of (a) the damage $f(t)$ for identical projections $l_0$ and (b) tangent of the slope of the damage curve $f(t)$ on $l_{0x}$ (for $f_0 = 2.45\%$)

Calculations show that (2)–(3) occur in a wide range of initial damage from 0.2% to 5%.

Thus, for the model it possible to obtain a simple approximate dependence $f(t, f_0, l_0, \alpha_0)$.

Experiments [1, 2, 7–11] have confirmed that the continuity of the material structure is restored, accompanied by a change in the volume fraction of microdefects (up to the complete healing of certain microdefects). The obtained results are in qualitative agreement with these experiments.

**Conclusions**

Metal damage decrease during HEEMF action leads to improvement of the plastic properties and increase ultimate plastic strain. Understanding the damage dependencies will allow determine constitutive equations for modelling electroplastic deformation and fracture processes. With the same initial material damage $f_0$, for changing material porosity during electric current pulse action the determining factors are not the geometry and microdefect orientation, but a generalized parameter equal to the projection of the initial “length” of the microdefect on the line (plane) perpendicular to the current density vector $l_{0x} = l_0 \cos \alpha_0$.

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