IUTAM Symposium on Growing solids
June 23-27, 2015, Moscow, Russia

Phase Transformations in Metals Stimulated by a Pulsed High-Energy Electromagnetic Field

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The application of electric current to difficult-to-form metal or alloy specimens makes their subsequent mechanical working easier, improves the plastic properties of the material, and has advantages over the traditional methods of thermal processing such as annealing etc. A well-known technological method that has long been in use is to heat the sample with electric current of low density $J \approx 10^2$ A/m^2 for a long time, $t \approx 10^3$ s. Studying the effect of electromagnetic field on the mechanical properties of conducting materials shows that the application of a short electric pulse with high density $J \approx 10^9$ A/m^2 and duration $t \approx 10^{-4}$ s can significantly (up to 4–5 times) increase the plastic strain to fracture. This phenomenon is known as the *electroplastic effect*, or *superplastic effect*. So far, there is no consensus about the nature and physical mechanism of this phenomenon, with fundamental hypotheses explaining it still being under discussion [1–5].

The electromagnetic field action on the deformation and phase transformations of an elastoplastic material with defects was studied. The electrotermomechanical process was stimulated by short high-energy electric pulses near plane cracks.

The dynamic problem was solved numerically for a representative element of the material with a microdefect (crack). The problem was solved in two stages by a finite element procedure. At the first stage, the thermal electrodynamic problem gives the distribution of electric potential, current density, temperature fields, and the phase transformation regions in the material. The phase transformations regions (melting and evaporation of the metal) were cross-calculated without the explicit allocation of the phase boundaries. At the second stage, a coupled unsteady thermomechanical problem was solved for the stress-strain fields in the heated elastoplastic representative element taking into account the change in the temperature field distribution in the material obtained at the first stage. A quasistatic thermomechanical problem was additionally solved to obtain the displacement field (the residual strain) after the temperature equalization in the material.

We show by a number of numerical simulations that a short high-energy electric pulse causes intensive local heating near defects, which leads to phase transformations in metal. For example, numerical modeling shows that large gradients of the electromagnetic field and current density can arise in the vicinity of microdefects, which leads to local melting and evaporation of metal in the microcrack tips. Under the action of thermal stress, the molten material flows into the microcrack. Simultaneously, the evaporation of metal takes place. The edges of the microcracks converge (Fig. 1). All this leads to defect healing (crack closing and material welding).

In addition, the influence of the size and orientation of

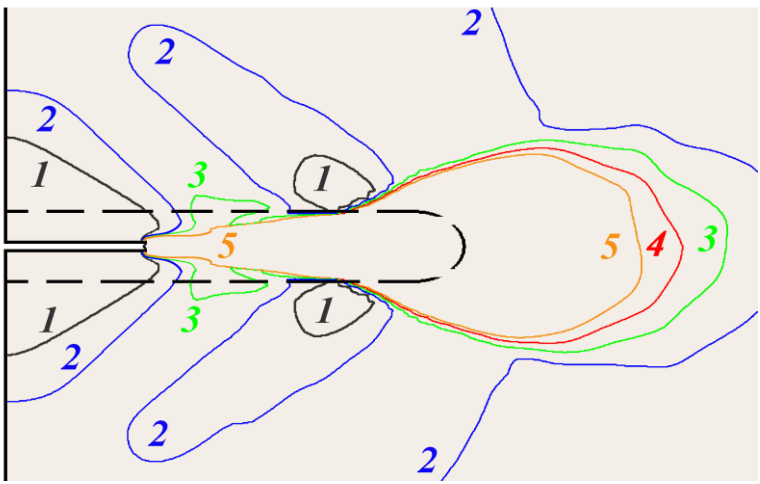

Figure 1: The microcrack at $t = 0$ (dashed thick line) and at $t = 27$ μsec (solid thick line). The equivalent plastic strain isolines at 27 μsec (black line *1* is 1%, blue line *2* is 3.75%, green line *3* is 6.5%, red line *4* is 9.25%, and orange line *5* is 12%).

microcracks on the localization of the electromagnetic field in the region of the defect are considered. We show by a number of numerical simulations for plane deformation that the size and orientation of microcracks does not affect the above-described phenomenon significantly in a fairly wide range of sizes (10–50 microns) and angles (0–20°). See Fig. 2.

The described mechanism contributes to a theoretical explanation for the experimentally established electroplastic effect of improving plastic characteristics of materials.

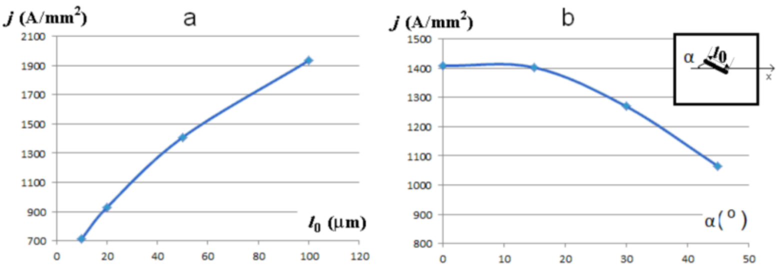

Figure 2: The dependence of the current density on the microcrack length (a) and slope (b).

This work was supported by the Russian Foundation for Basic Research (RFBR) under grant no. 15-08-08693.

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