Available online at www.sciencedirect.com

ScienceDirect

Procedia IUTAM 23 (2017) 84 – 100

Procedia IUTAM

www.elsevier.com/locate/procedia

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

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

Konstantin V. Kukudzhanov*, Alexander L. Levitin

Institute for Problems in Mechanics, Russian Academy of Sciences, 119526, pr-t Vernadskogo 101-1, Moscow, Russia

Abstract

Processes occurring in metals with microdefects when metallic specimens are treated by short high-density electric current pulses are considered. The variations in the electric and temperature fields in the material and their influence on the phase transformations and the stress–strain state in the vicinity of microdefects in the form of plane cracks with linear sizes of the order of 10 μm are studied. A mathematical model of the effect of an electromagnetic field on a predamaged thermoelastoplastic material with an ordered system of defects is proposed. The model takes into account melting and evaporation of the material and the dependence of all of its physical and mechanical properties on temperature. The solution of the resulting system of equations is sought by the finite element method on moving grids with the use of the combined Euler–Lagrange method. The dependence of the processes on the boundary conditions of the model is considered. We estimate the error that occurs when solving the problem for one representative cell rather than for the whole sample with an ordered system of defects. The influence of the distance between the cracks on the deformation and healing of microdefects is investigated. Numerical modeling has shown that a high-density current with large field gradients arises in the vicinity of microdefects, which leads to intensive local heating accompanied by thermal expansion and melting of the metal on the tips of the microcracks. This results in high compressive stresses near microcracks, intensive plastic flow of the material and, as a consequence, clamping of microcrack sides, decrease in microcrack length, and ejection of the molten material into the crack. As a result, the microcrack is completely healed. The numerical results obtained by the proposed model agree with experiments. Computations showed that if the distance between microcracks is equal to or greater than ten of their lengths, then the time for complete defect healing weakly depends on the distance between defects and the micro-defect interaction can be neglected. The interaction between microcracks in the metal significantly affects their healing process if the distance between them is reduced to about 5÷6 of microcracks lengths. With further decrease in the distance between the defects up to one microcrack length, the healing process does not change qualitatively, but slows down significantly: the ejection of molten material into the crack still happens, but the crack size reduction, especially in the transverse direction, is substantially smaller.

Peer-review under responsibility of the scientific committee of the IUTAM Symposium on Growing solids

* Corresponding author. Tel.: +0-000-000-0000 ; fax: +0-000-000-0000 .
E-mail address: kconstantin@mail.ru

Peer-review under responsibility of the scientific committee of the IUTAM Symposium on Growing solids
doi:10.1016/j.piutam.2017.06.008

Keywords: healing of microcracks; crack arrest; interaction of micro-defects; electroplasticity; high-energy electromagnetic field; short electric current pulse; localization; phase transition; melting; evaporation.

1. Introduction

Electromagnetic field energy has long been used in material forming. Induction or contact heating (due to the dissipation of electromagnetic energy) of a specimen by electric current with small density $\mathbf{j} \approx 10^{6} \mathrm{A/m^2}$ and long exposure time $\tau \approx 10^3$ s is a well-studied technological method for metal and alloy forming similar to annealing. This action leads to volume-uniform (integral) heating of the material to a temperature comparable with the melting point (usually $T \geq 0{,}6T_{\mathrm{melt}}$) and, as a consequence, to a decrease in the absolute values of its mechanical characteristics, including the yield stress, which simplifies processing of the heated blank. If the action of an electromagnetic field on a conductive material is intensive and short (by a current pulse with density $\mathbf{j} \approx 10^9 \mathrm{A/m^2}$ and action time $\tau \approx 10^{-4}$ s), then the surface temperature of the blank will change no more than by a few tens of degrees (depending on the exposure parameters and the material properties). Under this action, the elastic properties of the material remain almost unchanged (in contrast to integral heating), but the plastic properties are significantly improved: the yield limit is reduced, and the plastic deformation at fracture is significantly increased (from several tens to a hundred percent for various materials and alloys [Troitskii1985, Troitskii2010, Conrad2000, Beklemishev1986, KukudzhanovKolomiets-Romanenko2011, YeYangSongTang2014]). These improved plastic properties of the material are preserved forever rather than just during the action of the current pulse or immediately after it is finished (when the blank is still hot). This allows using this effect in production both simultaneously with machining and by alternating electrical and mechanical treatment. This phenomenon is known as *electroplastic effect*. The essential difference between the electroplastic effect and integral heating (or annealing) is that the increase in the plastic deformation limit due to the action of electromagnetic fields is caused by different mechanisms [Troitskii1985, Conrad2000, Troitskii2010, Beklemishev1986, KukudzhanovKolomiets-Romanenko2011, BeklemishevGorbunovKoryaginKukudzhanov1989].

This effect has been widely used in industry, especially for difficult-to-form materials such as high strength steels, titanium-, tungsten-, and magnesium-based alloys, conductive composites, ceramics, etc.

However, there is still no consensus about the nature of this phenomenon, and the discussion about its fundamentals and the physical mechanism is still ongoing [GoldmanMotowidloGalligan1981, Timsit1981, Troitskii1985, Beklemishev1986, KlyushnikovOvchinnikov1988, Ovchinnikov1989, Conrad2000, Troitskii2010, KukudzhanovKolomiets-Romanenko2011, YeYangSongTang2014, KukudzhanovLevitin2015].

Hypotheses explaining the electroplastic effect on the basis of concepts of solid state physics applied to metal monocrystals can be found in [Troitskii1985, Conrad2000, Troitskii2010, YeYangSongTang2014]. However, these hypotheses cannot explain the experimentally observed high plasticity of the material after the shut-off of the electromagnetic field, and they are also not consistent with other experimental data [GoldmanMotowidloGalligan1981, Timsit1981, Beklemishev1986].

One explanation of the electroplastic effect from the viewpoint of mechanics of solids is the hypothesis that the microdefects occuring in the material during the plastic deformation (which is carried out before or simultaneously with the action of the electromagnetic field) are healed (transformed) [Beklemishev1986, KlyushnikovOvchinnikov1988, Ovchinnikov1989, HuiZhong-jinGao2007, KukudzhanovKolomiets-Romanenko2011, KukudzhanovKolomiets-Romanenko2010, YeYangSongTang2014, KukudzhanovLevitin2015, BeklemishevGorbunovKoryaginKukudzhanov1989]. In these papers, the concept of healing is interpreted widely: healing is understood as melting of craters (pores) at the microcrack tips as well as the occurrence of compressive stresses near the crack tips and also the convergence of crack sides. This hinders further crack propagation, but the cracks themselves remain in the material.

It should be noted that, irrespective of the electroplastic deformation phenomenon, physical processes occurring near the tips of macrocracks (a few millimeters long) in thin plates under the action of electrical current pulses, as well as the possibility of healing of macrocracks, were studied in [FinkelGolovinSletkov1976, FinkelGolovinSletkov1977, KudryavtsevPartonRubinskii1982, PartonKudryavtsevRubinskii1980, CaiYuan1998, CaiYuan1999, Liu2008, Liu2010, Liu2013, Liu2014, YuZhangDengIqbalHao2013, YuZhangDengHaoIqbal2014].