EFFECT OF ELECTRIC CURRENT ON PRE-CRACKED THIN METALLIC SHEETS: FROM CRACK PROPAGATION TO CRACK HEALING

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Abstract

Recent studies have shown that the passage of electric current pulse may both, depending on pulse parameters, propagate and heal a crack in metals. Here, we discuss the reasons behind crack propagation upon application of an electric current and then explore the attributes responsible for a transition from flaw propagation to flaw healing upon passage of an electric current pulse. Furthermore, the synergetic role of mechanical load and magnetic field in propagating a pre-existing flaw upon application of an electric current pulse is also discussed.

1. Introduction

Both scientifically and technologically, it is important to study the effects of electric current pulses on the structural integrity of metallic components. As an electric current reverses its direction across a crack, massive current crowding occurs at the crack tip, generating a non-uniform temperature field sourcing away from the crack tip. Considerable electromagnetic forces are generated on the crack faces that open the crack in Mode I. Recent studies have shown that due to the synergistic effects of the above two stimuli, a pre-existing flaw may grow and heal upon application of an electric current pulse of high density. While one is a bane for structural integrity, the other is a boon to in-service components. Hence, it is critical to understand the conditions under which a crack would propagate and heal upon application of an electric current pulse.

Interestingly, although the literature demonstrates both effects of electric current passage, it neither provides conditions for the transition nor discusses the mechanics-and microstructure-based fundamentals of this transition. This work stems from the above literature gap. We also establish the complementary roles of electric current, magnetic field, and mechanical load in the failure and healing of pre-cracked metallic sheets.

2. Results

Finite element analysis (FEA) and supporting experiments were performed to gain insights into the effect of electric current, mechanical load and magnetic field, applied individually or simultaneously, on a metallic foil with an edge crack. FEA, performed using COMSOL Multiphysics, was used to solve Maxwell equations of electromagnetics to estimate the electric and the magnetic field distributions inside the metallic foil, the Lorentz law to estimate the electromagnetic force acting as a body force, the Joule's law of heating to estimate the temperature field, and the equations of equilibrium to estimate the distribution of stress and strain fields and, eventually, the J-integral and stress intensity factor. Realizing the limited role of plasticity during extremely short duration electric pulses, linear elasticity was assumed; however, temperature-dependent properties were used in FEA. Experiments involved testing pre-cracked Al thin foils (of ~10 µm thickness) and stainless steel sheets (of 1.5 mm thickness) using a custom-built setup, wherein numerous short electric current pulses (of pulse widths ranging from 50 µs to 10 ms) of high densities (> 10^9 A/m^2) were passed in succession while also applying a mechanical load and a magnetic field. A few tests were also performed while imposing out-of-plane tractions to inhibit the buckling of the thin sheets. Following tests, the sample was examined under an optical microscope and a scanning electron microscope to understand the extent of the crack propagation and the crack healing, depending on the phenomenon of interest. Electron backscattered diffraction (EBSD) analysis and mechanical testing were performed on the healed section of the sample to qualify the "degree" of the healing.

Figure 1 shows the current density, temperature, magnetic field, electromagnetic force and the corresponding von Mises stress when only electric current was passed through a sample with an edge crack. *Figure 1* clearly reveals the presence of Mode I loading on the crack tip, which can lead to the propagation of the crack (see *Figure 2*). Consistent with the numerical analysis performed using FEA, experiments revealed that applying an external mechanical load and a magnetic field reduces the current density required to propagate the crack.

Figure 2 also shows the healing of a pre-existing crack created by fatigue loading of a compact tension specimen upon application of several electric current pulses of relatively longer pulse width while also applying out-of-plane stress to preclude buckling. FEA simulation results show the prevailing of a compressive stress field near the crack due to the temperature gradient and a high-temperature field near the crack tip, both while acting simultaneously can lead to an effect similar to "diffusion bonding". In practice, the compressive stress field was augmented by an external mechanical load for crack healing at much smaller current densities.

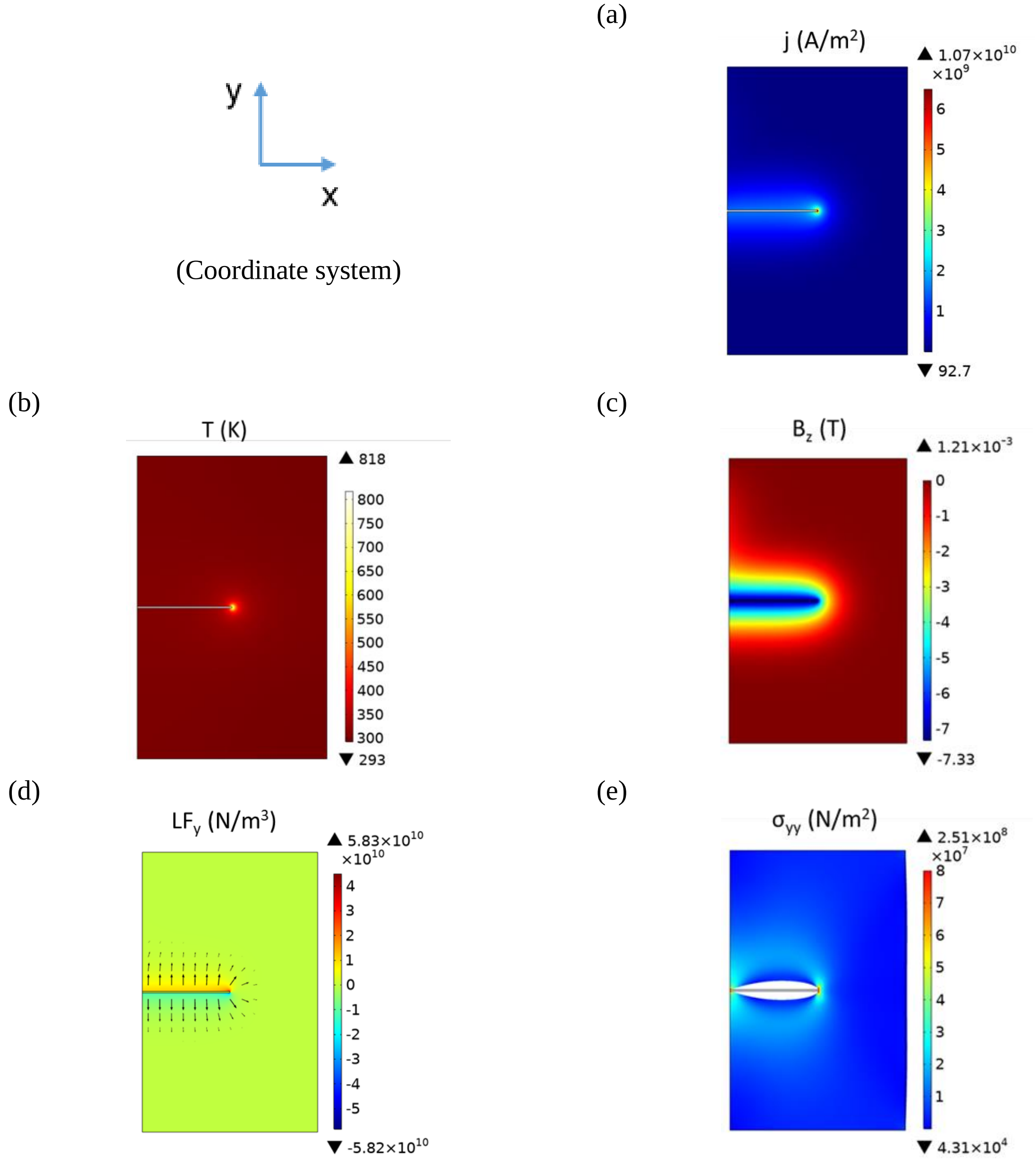
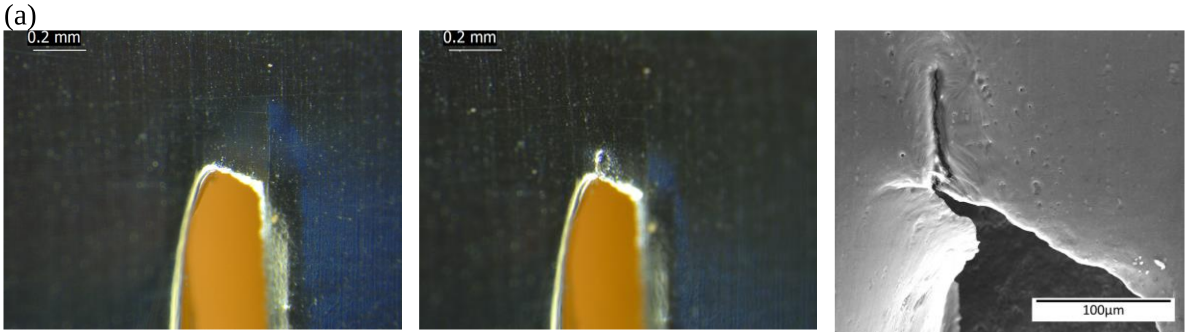


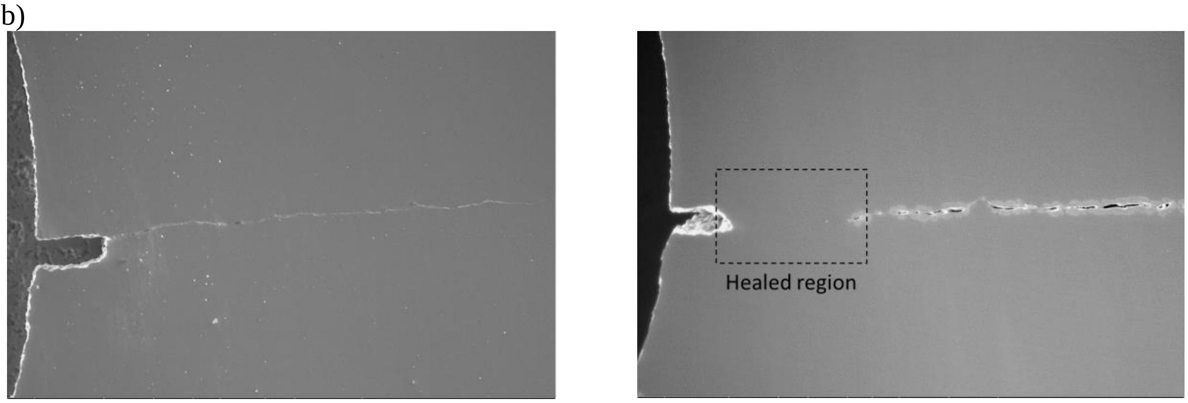
Figure 1. FEA results showing the distribution of (a) current density, (b) temperature, (c) out-of-plane magnetic field, (d) Lorentz force acting to open the crack in Mode I and (e) stress field and corresponding deformation (scale factor = 500) upon application of only electric current pulse through a thin sheet of Al comprising an edge crack. (Pulsing conditions: $j_{\text{app}} = 1 \times 10^9$ A/m^2, pulse width = 0.5 ms).

(a)



Initial Notch After 50 pulses Magnified view of the crack

(b)



Initial fatigue crack Partially healed crack

Figure 2. Experimental results showing the effect of electric current pulses on (a) propagation (Al: pulsing conditions: $j_{\mathrm{app}} = 1.29 \times 10^9$ A/m^2, pulse width = 0.5 ms, $a/W = 0.5$, 50 pulses) and (b) healing (stainless steel: pulsing conditions: $I_{\mathrm{peak}} = 4$ kA, pulse width = 200 ms, $a/W = 0.05$, 20 pulses) of a pre-existing edge crack.

3. Conclusions

1. Experiments proved that the self-induced electromagnetic forces alone could cause crack propagation in an edge-cracked foil, as the finite element analysis predicted.
2. The application of the external magnetic field and the mechanical loading decreased the critical current density required to initiate the electric current-induced fracture in pre-notched Al foil.
3. By incorporating the systematic change in the current pulse width and position of the electrodes (i.e., *a/W* ratio), crack healing conditions were achieved, and the crack propagated during fatigue was healed. Microstructural analysis revealed good bonding of the crack surfaces with less microporosity.
4. The crack propagation or healing due to the electric current pulses depended on the *a/W* ratio, width of the current pulse, and the material's electrical resistivity. Proper selection of these parameters can enable crack propagation or healing in the material.

Acknowledgments

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