Synopsis

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Title of the thesis: Synergistic effect of electromagnetic forces on the failure of pre-cracked thin metallic conductors.

Electric surges of large current densities, e.g., $>10^9 A/m^2$, often pass through components of various engineering systems, such as microelectronic systems, large scale integrated circuits, huge electromagnetic devices (for example rail gun, Tokamak fusion reactors, etc.), exposed metallic structures during lightning strikes (e.g., airplane, wireless towers, etc.), superconducting magnets, etc. Such high current densities, when passed through the components of these systems, can produce several effects, such as significant Joule heating, electromagnetic forces, electromigration flux, thermal stresses and shocks, etc. Since most of the engineering materials often contain defects like micro-cracks, micro-voids, etc, these high current densities may cause propagation of these flaws, resulting in failure of components by electric current alone, even if the component's design is safe with respect to the mechanical load or other constant and expected stimuli. Moreover, these applications also experience significantly large mechanical loads during their service time, which can further aid to the deterioration as well as catastrophic failure of the structure when an electric current surge is applied. Such a system where both mechanical stresses and electric currents are simultaneously presents poses a complex multi-physics electrical-magnetic-thermal-mechanical problem.

As shown in **Fig. 1.1**, when a potential difference is applied across a crack, the electric current essentially reverses its direction around the crack. The electromagnetic force associated with the self-induced magnetic field due to the current flow acts on the crack faces to open it in Mode I. The problem becomes more complex as the inhomogeneous current density around the crack also generates an inhomogeneous temperature distribution in the structure, especially in the region near the crack tip, causing excessive Joule heating. Therefore, whenever there is a reversal of electric current around a crack or an insulating discontinuity in a conductor, electromagnetic force tries to open-up the crack face in Mode I and Joule heating takes place at the crack tip.

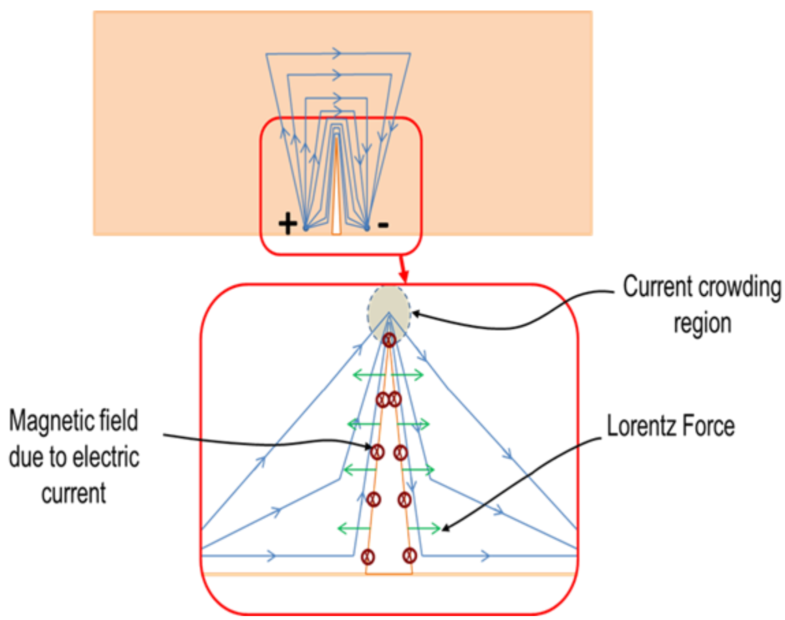


Fig. 1.1: Schematic illustration of reversal of electric current around an edge crack in a conductor upon application of a potential difference across the width of the crack. Electromagnetic force (or Lorentz force) induced due to interplay between electric current and self-induced magnetic field tries to open up the crack in mode I. Reversal of electric current around crack tip also causes current crowding in the vicinity of the crack tip which leads to Joule heating.

Moreover, due to excessive Joule heating generated by the current crowding at the crack tip, the material near the crack tip may undergo full or partial melting or even evaporation. Once the material is molten, it is removed or pushed away (sideways if only magnetic field in direction normal to the surface of conductor is present) by the electric current induced electromagnetic force (Lorentz force). This phenomenon is often termed as magnetic saw effect, which can form blow hole ahead of the crack tip. **Fig. 1.2a** to **Fig. 1.32d** show the blow hole formation ahead of crack tip in a conductor due to the magnetic saw effect.

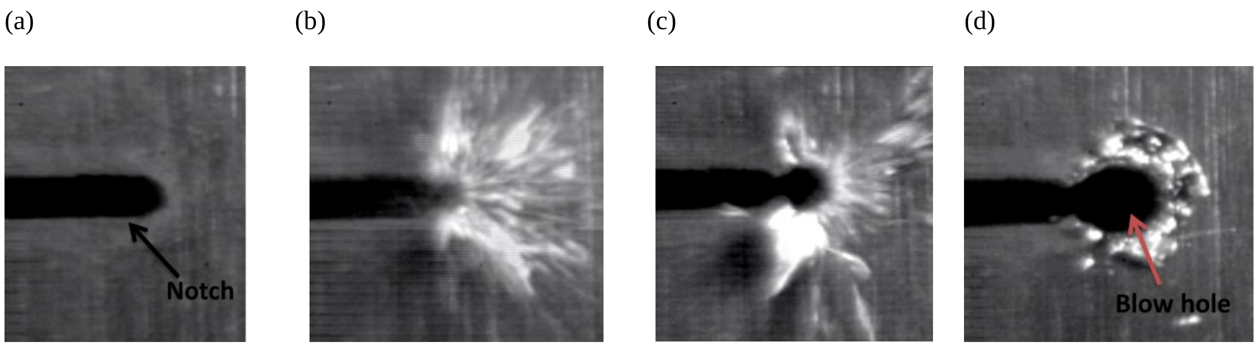


Fig. 1.2: (a-d) Time lapse photographs showing formation of a blow hole ahead of the notch tip in a conductor due to magnetic saw effect. The region near the notch vicinity is firstly, melted due to the Joule heating caused by excessive current crowding and subsequently, blown away by the electromagnetic forces, resulting in the formation of blow hole. (Ref: Gallo et al. Int. J. Fracture, 2011, vol. **167**(2): p. 183-193).

Herein, it is very critical to understand the importance of relative time scale of the electromagnetic forces and the magnetic saw effect in the propagation of flaw (e.g., crack) and material removal. Electromagnetic force is an “instantaneous” phenomenon which acts on the crack as soon as an electric current is passed, whereas material melts (i.e., as an aftereffect of heat spreading) only after a finite time. At first glance, this suggests that electromagnetic force is the only crack opening or flaw propagating agent during the initial stages of the flaw propagation, whereas the electromagnetic force and the magnetic saw effect simultaneously become significant only in the later stages of flaw propagation. *This hypothesis suggests a finite* *possibility for occurrence of the classic fracture in materials consisting a sharp crack due to the electric current only, and hence the existence of an electric current induced critical stress intensity factor*; the origin of this thesis work lies in the desire to understand the above.

In past a few decades, several researchers have investigated the effects of large current densities on a pre-cracked conductor; however, the classical propagation of crack (i.e., without significant heat affected zone and melting) upon application of self-induced electromagnetic forces alone or combined electric current and mechanical loading has never observed. This is mainly because a comprehensive study using thin samples or active cooling has never been performed so that effects of electromagnetic forces alone, (i.e., by alienating Joule heating and thermal effects), could have been studied. Accordingly, the present work was initiated for investigating the fundamentals of failure of pre-cracked metallic structures under electromagnetic loading and attempts were made to answer the following questions:

1. Can electric current alone cause crack propagation in metallic conductors? If yes, then can an independent self-induced electromagnetic force induced stress intensity factor be defined, and experimentally validated?
2. What is the role of Joule heating in the flaw propagation and failure of a structure? What are the conditions conducive to formation of a blow hole and transition from propagation of sharp crack to formation and propagation of blow hole?
3. How does crack propagation change when a mechanical load is simultaneously applied along with an electric current? How should the effective critical stress intensity factors due to an electromagnetic force and a mechanical load be calculated, and superimposed?
4. Can this apparent destructive failure phenomenon be used for some constructive applications?

Aforementioned questions were answered in the study by employing a 2-pronged strategy. Firstly, finite element method (FEM) simulations were performed, and distributions of current density, electromagnetic force, and stress fields due to the self-induced electromagnetic forces were evaluated in a pre-cracked thin conductor. Subsequently, experiments were conducted to validate FEM results, where a custom built experimental setup was designed that can apply (a) pulse electric current, and (b) a combination of electric current and mechanical load, at any angle between 0° to 90° relative to the crack, onto a pre-cracked thin sample. The experimental setup had the provision of conducting experiments at low temperatures by immersing the sample into a cold bath, such as liquid nitrogen.

A finite sized thin conducting plate with a center crack was investigated under the presence of an electric current. Firstly, to solve such a coupled multi-physics problem, a need for using numerical techniques such as finite element method (FEM) was highlighted in the study. Electric field in a thin conductor with a center crack was evaluated by performing 2-dimensional (2-D) FEM simulations and results were successfully bench marked against the available analytical solution. 2-D FEM simulations were further employed to investigate the stress distribution in a center cracked conductor due to the self-induced electromagnetic forces. Self-induced electromagnetic forces due to steady electric current produced significant Poisson's contraction as well as compressive σ_{xx} and σ_{yy} in the vicinity of the crack tip, resulting in closure of the crack in the center cracked conductor, as shown in **Fig. 1.3**. The observation was slightly different under transient or pulsed electric current loading, wherein the self-induced electromagnetic forces opened the crack at the beginning of the transient loading; however, here also these forces became compressive at latter stage of the loading and hence eventually acted to close the crack.

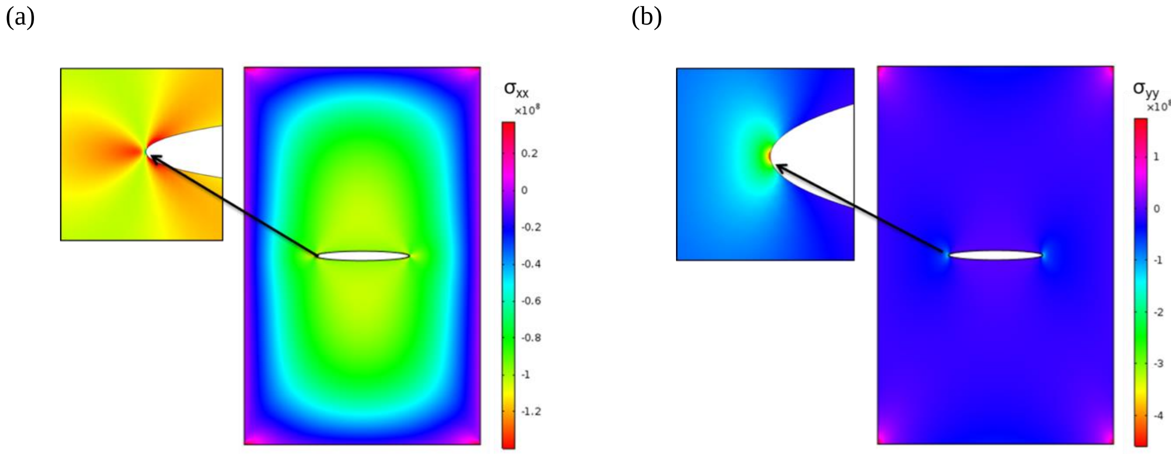


Fig. 1.3: FEM simulation showing the distribution of (a) σ_{xx} and (b) σ_{yy} in a thin conducting plate due to self-induced electromagnetic forces. Both σ_{xx} and σ_{yy} are compressive in the vicinity of the elliptical hole and try to close the crack.

Effect of passage of electric current through a finite sized conductor with an edge crack was further explored for observation of crack propagation. 2-D FEM simulations showed that self-induced electromagnetic forces due to passage of an electric current can open the edge crack a thin conductor, as shown in **Fig. 1.4a.** Static stress intensity in mode I due to the self-induced electromagnetic forces, K_{IE}, was observed to depend on current density, j, and crack length, a, as $K_{IE} = f(a/w)j^2(\pi a)^{0.5}$, whereas dynamic K_{1E} depended on j and a as $K_{1E,d} = f(a/w)j^2(a)^{1.5}$. To corroborate FEM results, experiments were conducted in an edge-cracked 12 μm thick Al foil sample. Short duration electric current pulses (without any external mechanical load), with pulse-width of 50 μs - 0.5 ms, of high current densities, ranging from 10^8-10^9 A/m^2, were passed and the resultant crack extension after each pulse was observed *in situ* using an optical microscope. Crack growth was observed in the sample due to pure electric current, as long as $K_{1E,d}$ was higher than the fracture toughness, K_{1C}, of the material, as shown in **Fig. 1.4b**. Moreover, crack propagated by a finite amount per electric pulse, and it became longer with continued loading.

Increase in current density and performing experiments at higher temperatures resulted in enhanced crack propagation.

(a) (b)

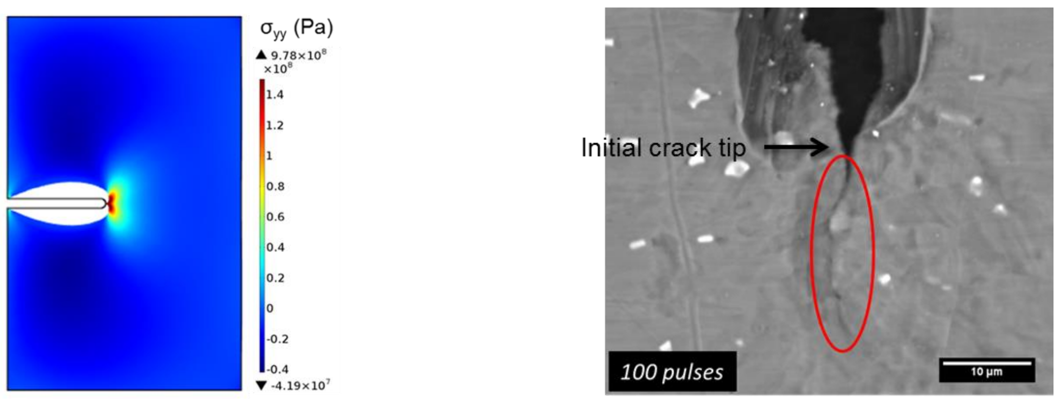
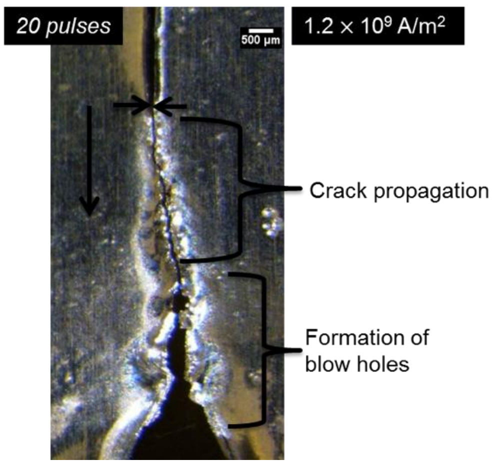


Fig. 1.4: (a) Distribution of σ_{yy}, as predicted by FEM simulation, for an edge-cracked thin conductor. The distribution is shown using the deformed shape of the model. σ_{yy} distribution ahead of the crack tip is tensile and tries to open up the crack in Mode I. (b) Propagation of sharp crack, encompassed by red ellipse, from initial crack tip, shown by horizontal arrow, after 100 short duration 0.5 ms electric current pulses of current density $j = 1.875 \times 10^9$ A/m^2. This result shows that self-induced electromagnetic forces alone can cause fracture in an edge-cracked conductor.

Experiments conducted under the conditions: (i) if normalized crack lengths were large (e.g., $a/w > 0.8$), and (ii) when electric current pulses of very high current densities (e.g., (> 2.08×10^9 A/m^2 for a/w of 0.7) were passed, revealed formation of blow holes, instead of incremental sharp crack, at the crack tip, as shown in **Figs. 1.5a** and **1.5b**, respectively. Upon repetitive electric current pulse loading the blow holes also propagated in a crack like fashion; however, average velocity of propagation of blow holes was much higher than the sharp crack propagation. At low current density blow holes propagated in a zig-zag manner with little splitting, whereas at higher current density it propagated in a straight path with large number of splitting, especially originating from the sharp tips of existing frontier blow hole. Formation of blow holes and their propagation was explained by performing microstructure based FEM simulations, which revealed that the formation of blow holes at one or multiple locations depends on the extent and severity of heat affected zone (HAZ). A direct correlation between the size of HAZ and the size of the blow hole as well as the propensity of formation of blow hole was established.

(a)



(b)

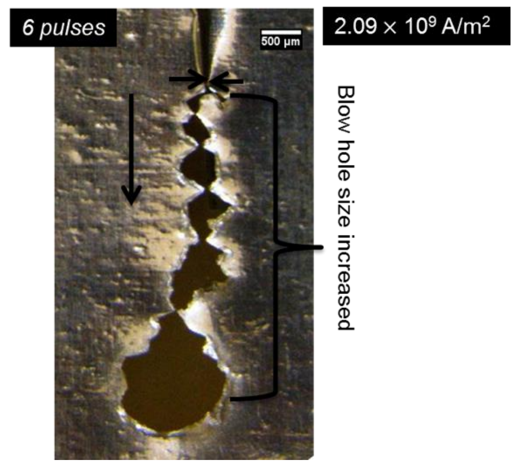


Fig. 1.5: (a) Sharp crack propagation and consequent blowhole formation in an edge cracked conductor with an initial crack length, *a/w*, *of* 0.7 at an electric current density of 1.2×10^9 A/m^2. The transition of crack propagation to formation of blow hole occurred at $a/w \approx 0.8$. The size of blowholes increased with each passed electric current pulse. (b) Formation of blowholes in an edge cracked conductor with $a/w = 0.7$ at a higher electric current density of 2.09×10^9 A/m^2. Here, increase in the current density caused the formation of blowholes at the original crack tip itself. The size of blowholes increased as the flaw length increased. The vertical thick arrow in both figures shows the direction of flow propagation. The original crack tip is shown by pair of horizontal arrows.

After understanding the effect of self-induced electromagnetic force on failure of pre-cracked conductors, effect of simultaneous electric current and mechanical loading on the crack propagation behavior in an edge-cracked conductor was explored. FEM simulation revealed that under combined electromagnetic and mechanical loading, the components of stress tensor as well as the stress intensity factors due to these two stimuli can be linearly superimposed to determine the overall stress tensor and stress intensity factor under combined electromagnetic and mechanical loading. Experiments conducted under combined electromagnetic and mechanical loading showed that the critical electric current density required to propagate a sharp crack decreased (see **Fig 1.6)**. Moreover, application of mechanical load at an angle to the crack faces (i.e., under mixed mode loading), deflected the crack at an angle upon passage of an electric current (see **Fig 1.6)**. The angle of deflection under mixed mode conditions was predicted by standard principles of mixed-mode fracture mechanics.

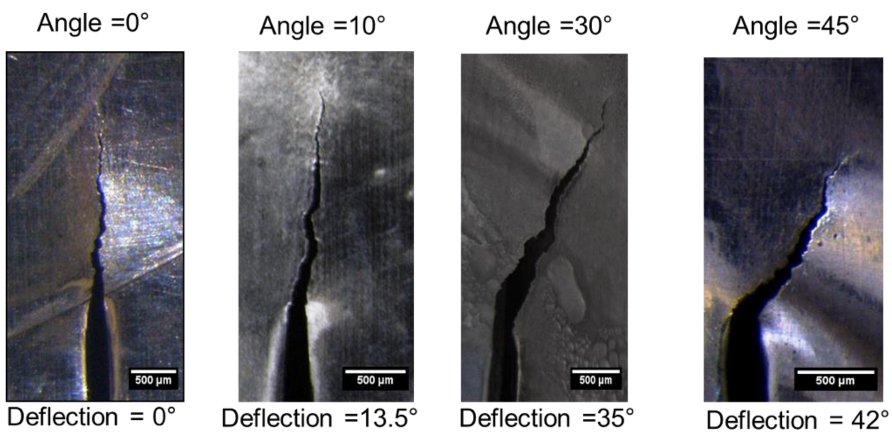


Fig. 1.6: Crack propagation under various mixed mode conditions due to the combined electric current and mechanical loading. The angle at top shows the angle at which mechanical load was applied relative to the mode I, whereas the deflection angle at the bottom shows the nominal angle at which the crack propagated relative to the original crack face.

Implications of the electric current surges of large current density, and simultaneous electromagnetic and mechanical loadings were also investigated in context of some real-life applications, such as interconnects in microelectronic devices and development of tool-less machining tool. Passage of electric current pulses of large current density caused catastrophic failure in both edge-cracked and center cracked 300 nm thick Cu thin films deposited on Si substrate, wherein failure features, such as severe melting in the vicinity of the crack tip, delamination of Cu film, splitting of cracks, and formation of blow holes, were commonly observed, as shown in **Fig.1.7**. A machining tool based on the electromagnetic-mechanical fracture was proposed as a constructive application of this rather destructive phenomenon, which can be used for machining thin metallic samples (≈12 μm) in any arbitrary shape with very high resolution (< 1 μm), as shown in **Fig.1.8**.

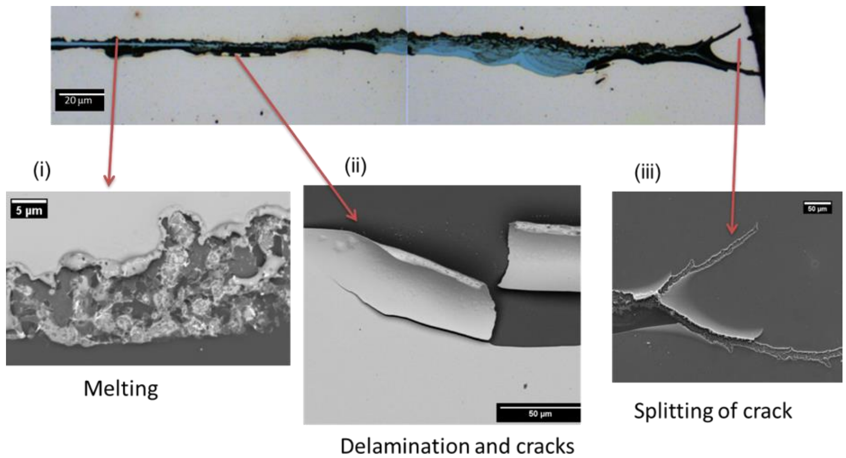


Fig. 1.7: Microstructural analysis of the failed edge cracked Cu thin film as observed under scanning electron microscope (SEM). SEM micrographs at different locations of the failed film show that the film failed by different mechanisms, such as (i) excessive melting, (ii) delamination and cracks (iii) splitting of cracks.

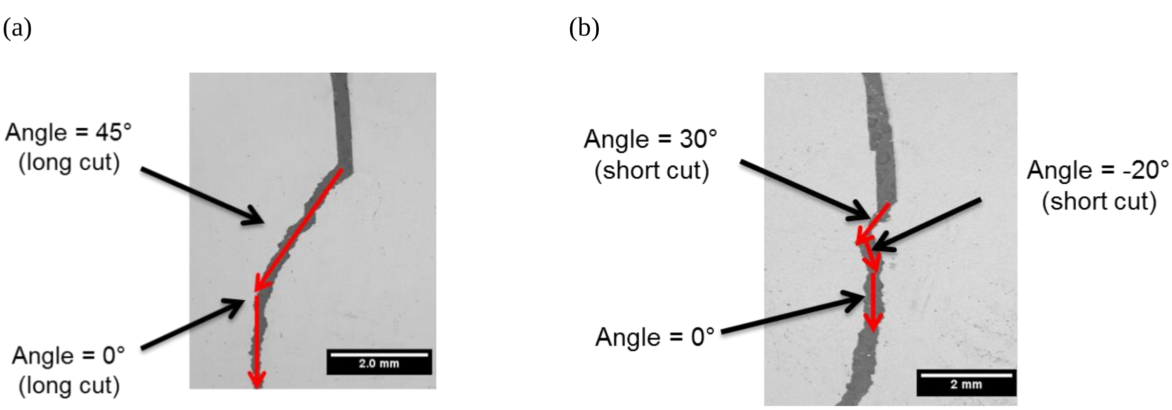


Fig. 1.8: Various shapes of cuts made in 12 μm thick Al foil by manipulating mode-mixity during combined electromagnetic-mechanical fracture: (a) Longer cuts and (b) shorter cuts. Shape and size of the cut depend on the number of electric current pulses passed and the direction of mechanical load relative to the crack face.