Synopsis

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Title of Thesis: Effect of Electric Current Pulses on Pre-cracked Thin Metallic Conductors: From Crack Propagation to Healing of Cracks.

Both scientifically and technologically, it is important to investigate the effects of electric current 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, thereby generating a non-uniform temperature field sourcing away from the crack tip, and considerable electromagnetic forces are generated on the crack faces that open the crack in Mode I (see - **Fig. 1**). Recent studies have shown that a pre-existing crack in a conductor can propagate due to the tensile stresses generated near the crack tip as well as heal due to simultaneous presence of compressive stresses upon application of an electric current pulse of high density. The crack propagation due to electric current is a structural integrity concern in applications where the current densities of the order of 10^8 A/m^2 often pass through the material (such as railguns, Tokomak fusion reactors, microelectronics, etc.,). Moreover, these applications also experience external magnetic field and mechanical load in addition to pure electromagnetic loading, which may further lead to deterioration and catastrophic failure of the component. On the contrary, electric current-induced crack healing can aid in extending the life of the in-service components with surface and subsurface cracks.

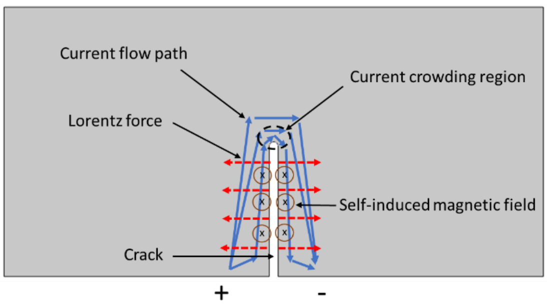

Fig. 1: A schematic illustrating the reversal of the electric current around an edge crack in a conductor when a potential difference is applied across the crack. The electromagnetic force (i.e., the Lorentz forces, shown by broken red arrows), generated by the interplay between the electric current (shown by solid blue arrows) and self-induced magnetic field (shown by the symbol "⊗"), opens the crack in Mode I. The area "near the crack tip" where the current becomes concentrated near the crack tip is indicated by a broken black ellipse.

Interestingly, a connection between the two effects namely, crack propagation and crack healing caused by a single stimulus (i.e., electric current) is not yet established. Hence, the main aim of this work was to understand the connection between crack propagation and healing caused by the passage of electric current in a conductor comprising a crack and derive the conditions leading to crack propagation and crack healing. Further, in this process, the study addressed the gaps in the literature concerning the effect of external fields on the fracture behavior of thin metallic conductors. Additionally, the study explored the possibility of complete solid-state crack healing in a metallic conductor, owing to the high-temperature field and the compressive stresses near the crack tip, with precise control of the process parameters which has not been studied before. Specifically, this study aims to:

1. To understand the attributes leading to crack propagation and crack healing in a pre-cracked metallic conductor due to the passage of an electric current pulse.
2. To understand the influence of external magnetic field on fracture behavior of pre-cracked current carrying thin metallic conductor.
3. To expand the knowledge of crack deflection to develop an application towards toolless machining of thin metallic conductors by application of combined electromagnetic and mechanical loading.
4. To develop a comprehensive understanding of electric current-induced crack closure and solid-state material healing in pre-cracked metallic conductors.
5. To understand the effectiveness of solid-state crack healing in terms of the mechanical performance of the healed metallic conductors.

Initially, a conducting plate with an edge crack was investigated under the influence of electric current using the finite element analysis (FEA) to understand the variation of the distribution of the tensile and the compressive stresses near the crack tip in a thin metallic conductor with the electro-pulsing and sample parameters. The FEA predictions revealed that crack propagation might be possible in a relatively high conductive material (e.g., Al, Cu), having a longer pre-existing crack, when the electric current of shorter pulse width is passed through the conductor. Similarly, crack healing might be possible when an electric current of sufficiently larger pulse width is passed through a short crack containing conductor with a relatively high electrical resistivity (see **Fig. 2**). Hence, to validate these findings, the crack propagation and healing were studied in pure Al (a high conductivity metal) and austenitic stainless steel SS316 (a low conductivity alloy), respectively.

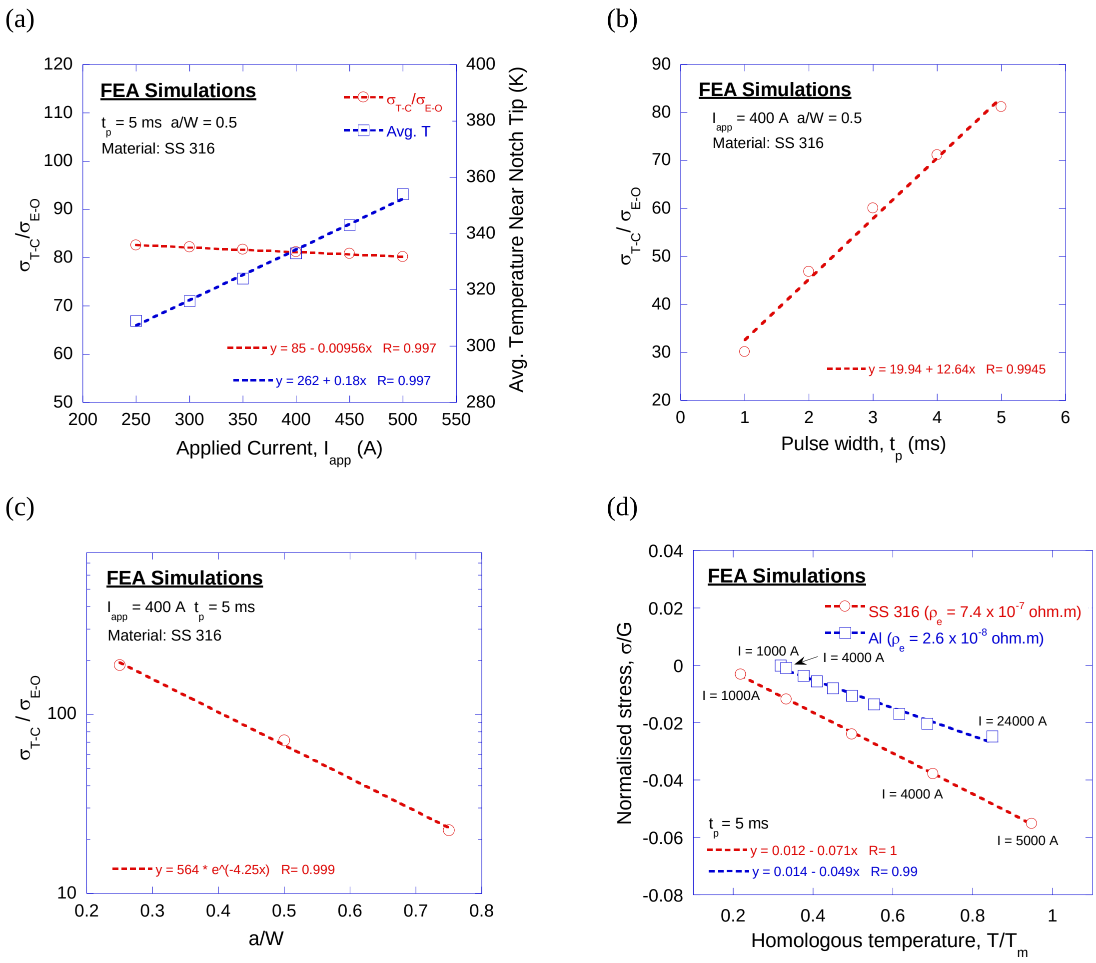

Fig. 2: Dependence of $\sigma_{T\text{-}C}/\sigma_{E\text{-}O}$ ratio on the electric pulse and sample parameters: Effect of (a) applied current, I_{app}, (b) pulse duration, t_p, and (c) a/W ratio and, equivalently crack length, a, on the ratio of thermal compressive stress, $\sigma_{T\text{-}C}$, and electromagnetic tensile stress, $\sigma_{E\text{-}O}$. The curve-fitting equations are shown in the legend, wherein R represents the curve-fitting regression parameter. A value of R closer to 1 for all cases indicates excellent curve fit. (d) Variation of the stress generated near the crack tip normalized by dividing with the room temperature shear modulus as a function of the corresponding homologous temperature, T/T_m, where T_m is melting temperature, for two materials (Al and SS 316) having significantly different electrical resistivities (ρ_e). The room temperature electrical resistivities of Al and SS 316 were considered in the study. It should be noted that $\sigma_{T\text{-}C}$ and $\sigma_{E\text{-}O}$ were calculated 50 μm away from the notch tip. The average temperature was calculated for the region of 100 μm in the vicinity of the crack tip.

In the first part of the work, the effect of a uniform external magnetic field on the fracture behavior of 11 μm thick pre-notched Al foil carrying current was explored. Experiments were conducted by subjecting Al foil to a series of electric current pulses in the presence of an external magnetic field up to 1 T. Sharp crack propagation was observed, and the critical current density required to initiate crack propagation decreased linearly with the external magnetic field, as shown in **Fig. 3**. Further, FEA was performed to gain insights into the interactions of the self-induced and the external magnetic fields and in turn their effect on the electromagnetic stress acting near the crack tip. An expression for the stress intensity factor generated due to the electromagnetic loading in the presence of an external magnetic field was established. Furthermore, the transient stress intensity factor, $K_{IE,t}$, calculated for the critical combination of applied nominal current density and external magnetic field demonstrated a reasonable match with the plane stress fracture toughness, K_{IC}, confirming the classic fracture condition of critical $K_{IE,t} \geq K_{IC}$ for lower levels of external magnetic fields ($B_{ext} < 0.4$ T) and for smaller crack lengths ($a/W < 0.55$), where a and W are the crack length and width of the conductor, respectively. Interestingly, the crack initiated at $K_{IE,t} < K_{IC}$ in case of higher external magnetic fields and longer crack lengths. This was consistent with the occurrence of undulations near the crack faces induced due to local buckling. Furthermore, a comprehensive understanding of the effect of local buckling on the stress state and mode mixity near the crack was developed and the underlying reasons for the crack initiation below K_{IC} were discussed.

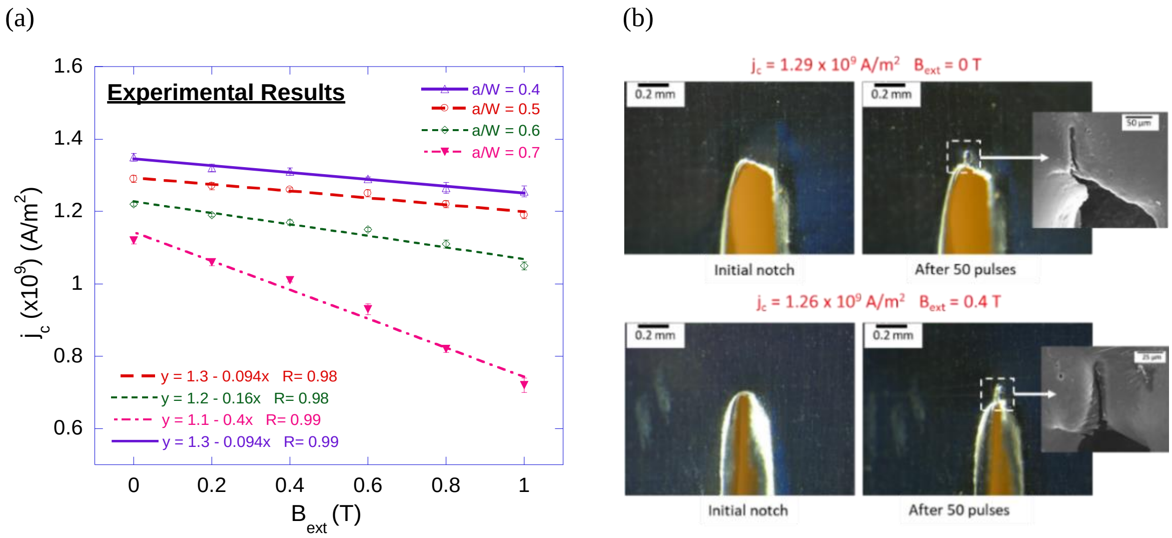

Fig. 3: Effect of the external magnetic field, B_{ext}, on the crack initiation and propagation in a current carrying pre-notched 11 μm thick Al foil: (a) Variation of the critical current density required to nucleate and propagate a crack from the notch tip, j_c, as a function of the external magnetic field, B_{ext}, (b) Optical micrographs demonstrating crack initiation from the notch after the passage of 50 current pulses for two critical combinations of applied current density (j_{app}) and external magnetic field (B_{ext}). The inset shows higher magnification SEM micrographs, revealing the presence of a sharp crack originating from the notch, with minimal spread of a heat-affected zone.

Additionally, a detailed microstructural examination of the fracture surface of the thicker Al foils (25 μm and 100 μm) revealed considerable thinning before the final fracture under pure electromagnetic and in combination with mechanical loading, indicating plane stress fracture. Further, the foil fractured by the application of combined electromagnetic and mechanical loading revealed a dominant transgranular fracture (see **Fig. 4a**). After developing an understanding of the interactions of the pure electromagnetic loading with the external mechanical loading, a fully automated toolless machining setup was designed and fabricated to machine thin metallic conductors by controlling the crack propagation direction (i.e., the angle of crack deflection, θ, and the length of crack propagation, Δa). The setup enabled the simultaneous application of electric current pulses and far-field mechanical loading at various angles ranging from -60° to 60° with respect to normal of the crack faces. A wavy crack propagation resembling a sinusoidal pattern was demonstrated in 25 μm thick Al foil as a result of the in-plane mixed mode fracture caused by the interplay between the electromagnetic and mechanical loading (see **Fig. 4b**). FEA provided further insights into controlling the crack propagation process by estimation of the Mode I and Mode II stress intensity factors and the associated crack deflection angle. Interestingly, the observed crack deflection angles showed a decent match with the estimated crack deflection angle (based on LEFM). Finally, the effect of the relative fraction of the electromagnetic and the mechanical loading on the machining resolution was discussed.

(a) (b)

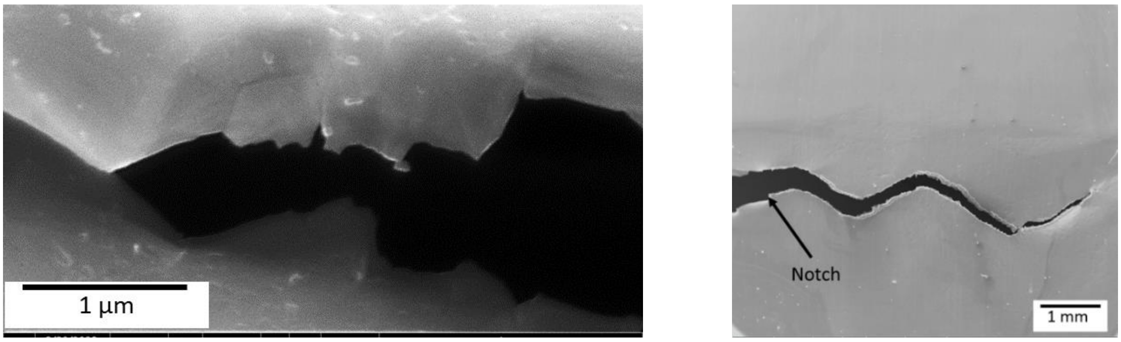

Fig. 4: Fracture of Al foil under combined electromagnetic and mechanical loading: Scanning electron micrographs showing (a) transgranular fracture with a small fraction of intergranular nature, (b) a sinusoidal pattern machined by controlled crack propagation by application of mechanical loading at various angles with respect to crack faces in the Al foil using custom-built toolless machining setup.

Further, the study expanded the understanding of crack healing upon passage of an electric current pulse. The electro-pulsing parameters were optimized to create diffusion bonding conditions (i.e., significant compressive stresses and appropriate temperature) near the crack faces using FEA. The conjugate experiments performed on SS 316 revealed complete healing of a through-thickness fatigue crack due to high-density electro-pulsing, as shown in **Fig. 5a**. A detailed microstructural analysis of the healed region revealed significant interface boundary migration and formation of cell structure (see **Fig. 5b** and **c**), thus signifying diffusion or solid-state bonding as the primary bonding mechanism. In addition to elucidating the role of the thermal effects of electric current on the healing process, the study also thoroughly discussed the influence of athermal effects, such as electroplasticity and electromigration. Furthermore, the effectiveness of the healing in terms of mechanical performance was explored by performing uniaxial tension, fatigue, and nanoindentation tests. The commendable mechanical properties of the healed samples, especially after solution annealing were observed owing to the excellent healing of the crack faces achieved in the study.

(a)

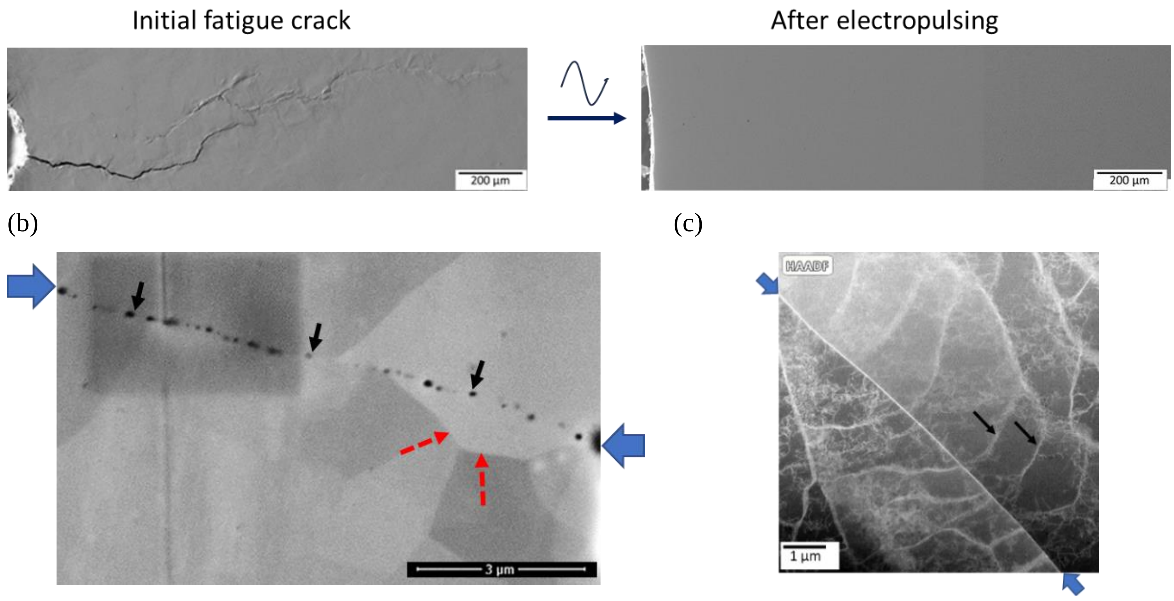

Fig. 5: Electric current-induced healing of cracks in SS 316 sheet: (a) scanning electron micrograph showing complete crack healing after electropulsing, (b) an instance of interface boundary migration in a partially healed sample. The solid black arrows indicate the microvoids and the red dashed arrows indicate the migrated interface, (c) STEM – HAADF micrograph showing the formation cell structure near the healed interface. The wide blue arrows in (b) - (c) indicate the position of the original interface.

Overall, the developed understanding in this work sheds light on the attributes leading to crack propagation and healing caused by electric current by a systematic numerical and experimental coupled approach.