EXPLORING THE PHNOMENOLOGY AND GOVERNING MECHANISMS FOR THE LOADING RATE DEPENDENCE OF ENVIRONMENTALLY ASSISTED CRACKING IN STRUCTURAL ALLOYS

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Abstract
While literature indicates that the applied loading rate (dK/dt) can affect environmentally assisted cracking (EAC) behavior, the quantification of dK/dt dependencies and mechanistic understanding of why the applied dK/dt influences EAC remain limited. In this study, a slow-rising stress intensity (K) framework was utilized to measure EAC kinetics over dK/dt ranging from 0.2 to 20 MPa√m/hr in Beta-C Ti, AA7075-T651, AA5456-H116, Monel K-500, 304L SS, Pyrowear 675, and Custom 465-H900 stainless steel immersed in 0.6 M NaCl at applied potentials known to promote modest EAC susceptibility. Results demonstrate that the crack growth rate (da/dt) exhibits two characteristics regimes of behavior with increasing dK/dt across multiple alloys. In particular, a 'plateau' regime where da/dt is independent of dK/dt was observed for elevated dK/dt, while a 'linear' regime where da/dt linearly scales with dK/dt was noted for slow dK/dt. These findings are analysied in the context of stress- and strain-controlled failure criteria and the environmentally modified Ritchie-Knott-Rice criteria for crack advance. The implications of these findings on recent testing standardization efforts for HEAC are then discussed.

1. Introduction
Structural metals exposed to hydrogen (H) suffer from decreased performance that manifests as reduced ductility and fracture strength, enhanced crack growth rates, and the onset of sub-critical crack growth at stress intensities (K) less than 10-20% of the reported fracture toughnes. This H-induced degradation in mechanical properties compromises structural integrity frameworks, which can lead to the unexpected, premature failure of critical components. To this end, numerous experimental protocols have been developed and standardized to assess the EAC susceptibility of structural metals, including: NACE MR0175, NACE TM0198, ASTM G30, ASTM G39, ASTM G12, ASTM E1681, ASTM F1624, I 7359-7, and ISO 7539-9. The generation of fracture mechanics-based EAC da/dt vs. K relationships could enable extension of the robust structural management approaches utilized in the fatigue community to manage EAC; an example of such an approach has been detailed by Gangloff. However, any fracture mechanics approach is predicated on the rigorous and/or conservative transfer of laboratory data to loading and environment conditions pertinent to component operation. Literature establishes that the applied loading rate used during LEFM testing can have a significant impact on obtained EAC metrics, indicating that variations in loading rate could potentially compromise fracture mechanics similitude.

2. Methods
Fracture mechanics testing at a monotonically increasing elastic K (dK/dt) was achieved by coupling active crack length measurement *via* dcPD with software-controlled, servo-hydraulic actuator displacement. This approach enabled testing that maintained a specific K vs. time profile. Single edge notch tensile (SEN(T)) fracture specimens of Beta-C Ti, AA7075-T651, AA5456-H116, Monel K-500, 304L SS, Pyrowear 675, and Custom 465-H900 stainless steel are tested in immersed in 0.6 M NaCl at applied potentials known to promote modest EAC susceptibility. Of note, is that the material systems and environments capture a broad variation in strength, H diffusivity, governing damage mechanism (e.g. H-embrittlement, anodic dissolution, etc.), and crack tip oxide formation.

3. Results

The most notable result is that for all alloy systems a positive dK/dt loading protocol provided a conservative and efficient rendering of the EAC susceptibility. This practical finding is critical in supporting the generation of a new ASTM standard for EAC characterization and suggests that legacy constant- or decreasing K protocols are non-conservative for modestly suceptibile material/environment combinations.

More fundamentally it was observed that highly suceptibile material/environment combinations were generally loading rate independent and was operating in a diffusion mediated and stress-controlled failure regime. The modest material/environment combinations resulted in significant loading rate dependence and operate under a strain-controlled regime where the growth kinetics are mechanics mediated. Two regimes of da/dt dependence on dK/dt were noted: (1) a linear increase of log(da/dt) with log(dK/dt), and (2) a plateau in the da/dt at higher dK/dt values (Figure 1). R-curve type analysis was used to provide further justification for the evolution of the material resistance (and thus the da/dt response) in the two regimes.

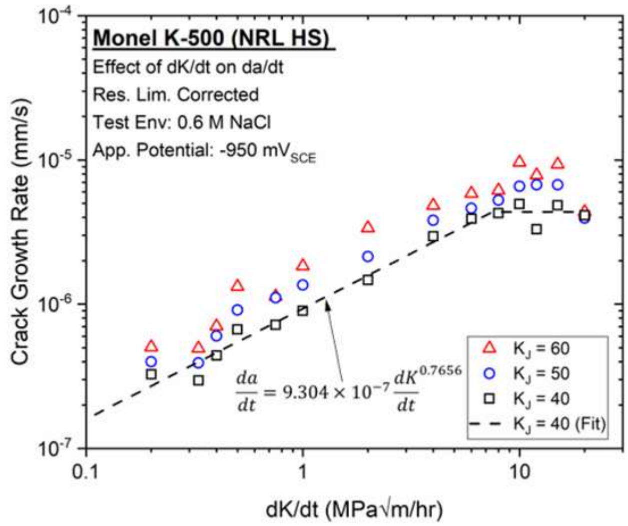

Fig.1 – Variation in resolution limit-corrected da/dt with dK/dt for three K_J values. The sloped portion of the black dashed line corresponds to a power law fit of all dK/dt ≤ 8.0 MPa√m/hr for K_J of 40 MPa√m.

4. Conclusions

Positive loading rate testing results in conservative characterization of EAC behavior across a wide range of structural alloy systems.

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