Joint AFRL – FAA Technical Interchange Meeting (TIM) on Environmentally Assisted Cracking (EAC) of High-Strength 7XXX Series Aluminum Alloys

Updated March 2025

Table of Contents

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AFRL

AFRL Perspective and Experience with Unexpected Environmentally Assisted Cracking in 7XXX Alloys

Materials and Manufacturing Directorate

C. Hunter, A. Rosenberger, K. Wertz

We asked each of you the following questions….

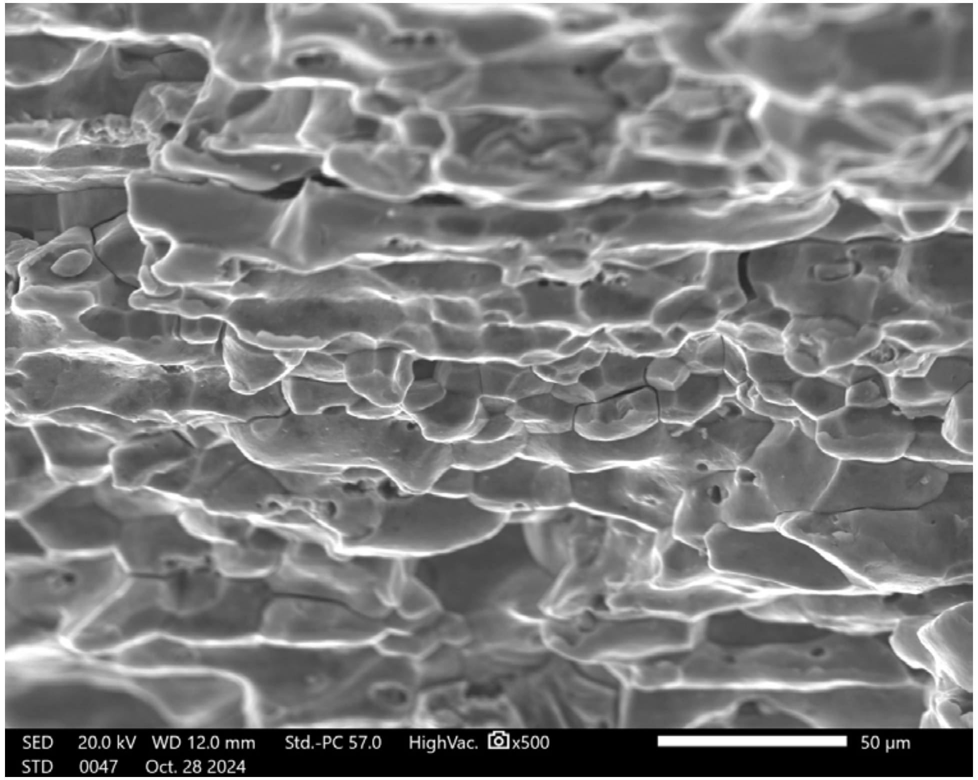
1. How has your organization bounded the problem definition of unexpected cracking in 7XXX aluminum alloys in service? If possible, provide a brief explanation and examples in a pre-competitive format.
2. What key influencing factors are suspected for the damage mechanism(s) identified above (e.g. humidity, temperature, steady-state stress, other)?
3. What are the 3-5 most critical questions that you think need to be answered?
    - What are your hypotheses about the problem and potential solutions to that problem?
    - Does your organization have the resources to answer the 3-5 questions?
    - If so, what is the timeline to address the 3-5 questions?
    - Will this information be shared with the community? How would the community validate your work so it can be used to the greatest impact?
    - Do you foresee any significant challenges with translating research results into practical applications (e.g. predictive modeling or the establishment of threshold criteria)?
4. What suggestions does your organization have for a community-wide standardized test to address the cracking problem, and could it be used as part of the material qualification/certification process?
5. Is there a suggested path forward for new alloy development?
6. Do you have suggestions for preferred community-wide collaboration mechanisms to share research progress or engineering solutions?

…and here are our answers:

Bounding the Issue

How has your organization bounded the problem definition of unexpected cracking in 7XXX aluminum alloys in service? If possible, provide a brief explanation and examples in a pre-competitive format.

- Unexpected intergranular cracking has been observed on several USAF platforms (7085-T7452 forgings, others)
- Occurred in 7XXX alloys explicitly identified in EASA SIB-2018-04. Comparative fractography exhibited features similar to those shown in EASA bulletin
- Cracked components were not exposed to atypical service environments
- Sustained stress thought to be well-characterized – considered superposition of residual manufacturing, installation, and service stresses (*)
    - ASK: Any known experiences where EAC observed below published SCC thresholds?
- Material selection assumptions have been called into question due to these and other reported findings across the community



Critical Questions

What are the 3-5 most critical questions that you think need to be answered?

- What is the best method to manage the lives of high-strength aluminum alloy components in aerospace applications?
- Does an effective test for EAC sensitivity exist that provides for use of high-strength aluminum alloys? Or does the community need to develop it?
- Under what conditions do environmentally-assisted cracks arrest?

Does your organization have the resources to answer the 3-5 questions?

- No, but have initiated exploratory efforts (discussed on next slides).

Will this information be shared with the community? How would the community validate your work so it can be used to the greatest impact?

- Yes, plan to publically release all findings to the extent possible.

Approach

Current Industry Standard Testing	Actual Damage Mechanisms	Known Influence Factors
Accelerated. Ex: ASTM G44/G47 Aggressive Saline Environment	Service environments typically less aggressive Cl- concentrations. Local crack tip environment unknown.	Each mechanism may have unique response to known variables.
"Whole Life": Combined Effect of Multiple Mechanisms	Crack Incubation *Think: Corrosion Pitting*	Composition, Microstructure, Stress, Environment
	Crack Initiation *Think: Large Pits to Crack*	Composition, Microstructure, Stress, Environment
	Small and Short Crack Growth *Think: Crack Growth at Microstructure Length Scale*	Composition, Microstructure, Stress, Environment
	Long Crack Growth *Think: Crack Growth as Bulk Material Property*	Composition, Microstructure, Stress, Environment

AFRL Supported Research on Unexpected EAC

EXPLORATORY EFFORTS ON “MODEL” ALLOYS AND PRODUCT FORMS:

1. Explore long crack growth rates as a function of environmental conditions (temperature and humidity) comparing a “susceptible” alloy 7085-T7452 to “non-susceptible” 7050-T7451. Effort will be accompanied by fractography and full material characterization (e.g. bulk and grain boundary). Additionally explore crack pre-cursor differences via a series of electrochemical polarization studies.

2. Perform crack arrest study on above alloys to test the hypothesis that EAC initiated cracks will not grow when local mechanical driving forces fall below the threshold stress intensity.

3. Investigate shortcomings of ASTM G47/ASTM G44 for current issue.

RESULTS TO BE SHARED PUBLICALLY.

These studies are funded; estimated completion date is Dec 2025.

Proposed Community-Wide Collaboration

Do you foresee any significant challenges with translating research results into practical applications?

- Challenge: Arrive at community consensus for new test methodologies + publish industry standard
- Challenge: Identifying and understanding mechanisms sufficiently to allow for management of in-service components
- Challenge: Discern the limits of applicability for current standard test methods (i.e. when are the ASTM G47/G44 test methods appropriate?)

Proposed Collaboration Ideas

Suggest TIM become an annual event with potential virtual check-ins at six month intervals to share on-going results and insights.

We didn't address all the questions…

1. How has your organization bounded the problem definition of unexpected cracking in 7XXX aluminum alloys in service? If possible, provide a brief explanation and examples in a pre-competitive format.
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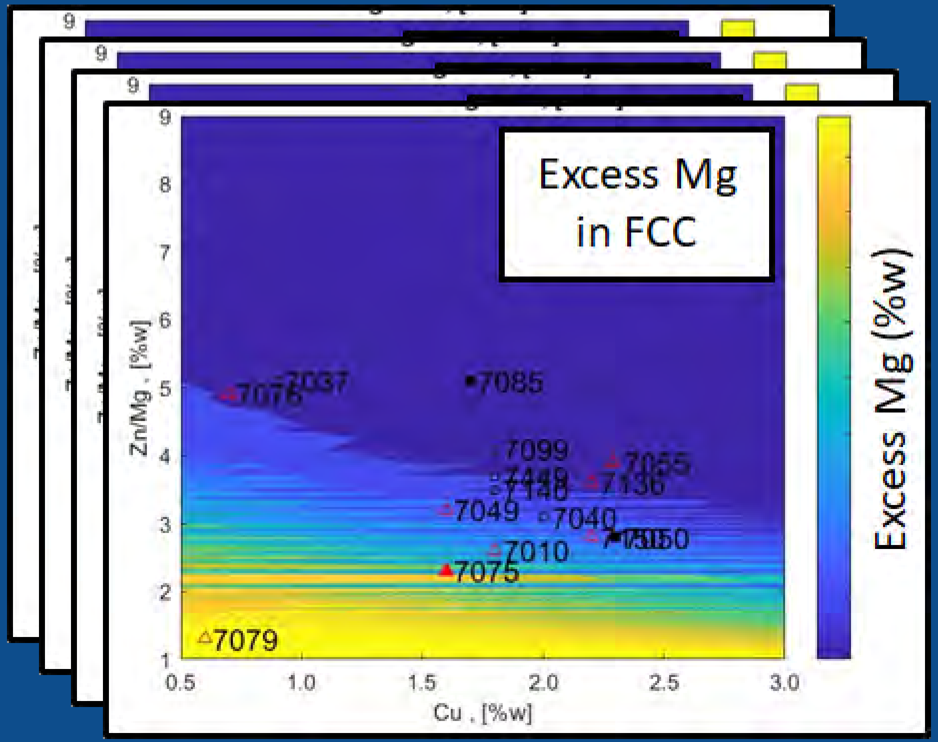
…still a lot of unknowns.

Thank you!

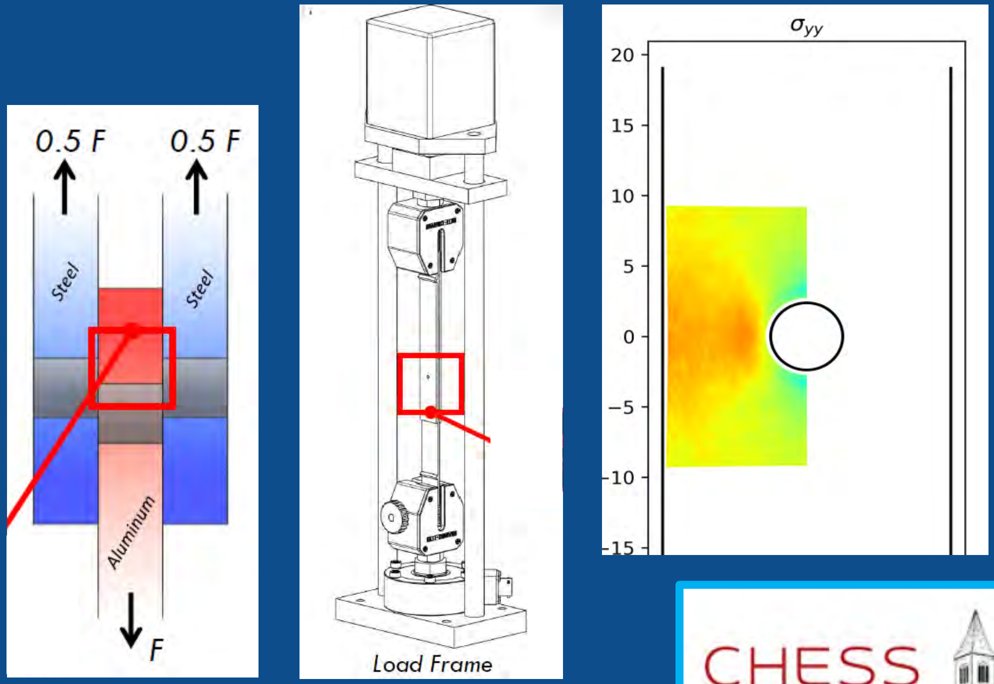
AFRL Research on Unexpected EAC

Thermodynamic (CALPHAD) Assessment "Sensitive" Alloys identified in EASA SIB 2018-04



"Proof-of-Concept" Stress Measurement Technique at CHESS Synchrotron

High-fidelity stress measurement of double blind joint connected via interference fit



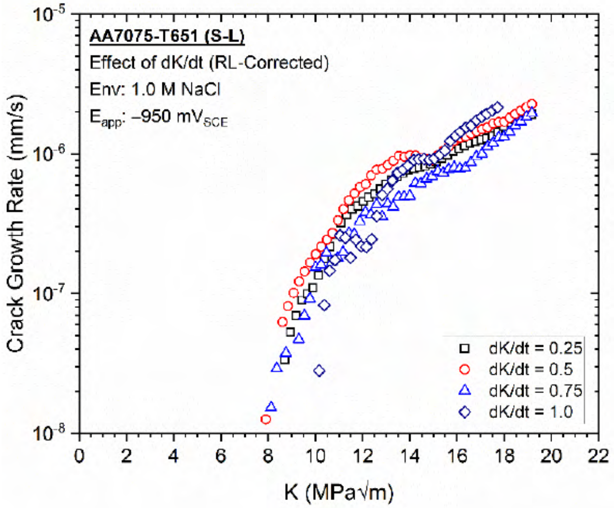
AFRL Supported Research on Unexpected EAC

UNIVERSITY of VIRGINIA

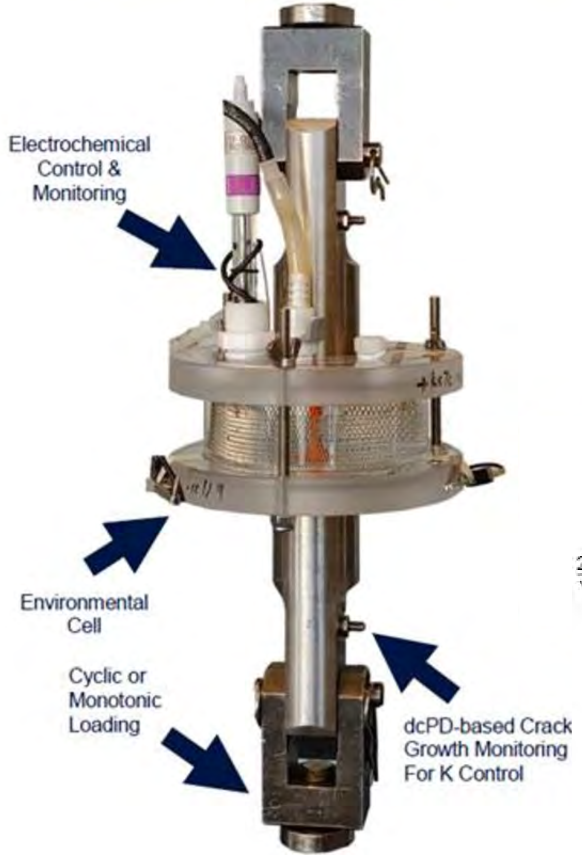
Explore long crack growth rates as a function of environmental conditions (temperature and humidity)

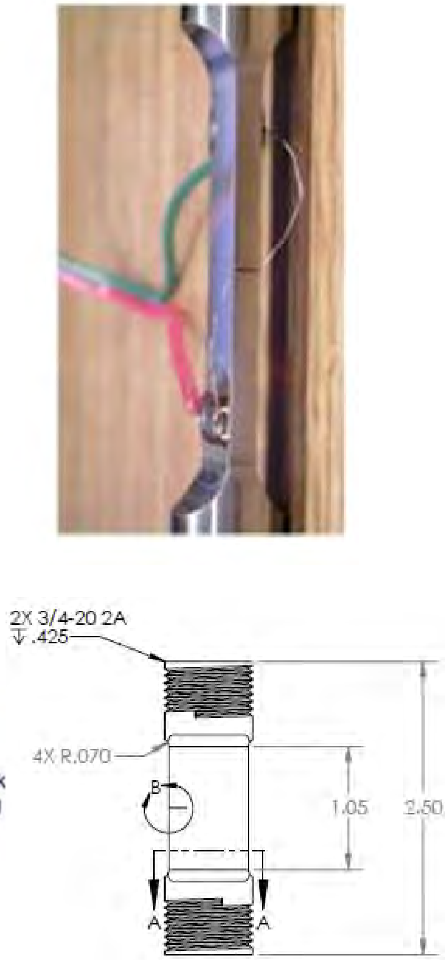
"Susceptible" 7085-T7452
"Non-susceptible" 7050-T7451

Temp	%RH	H_2O (kPa)	H_2O (g/m^3)
85°C	85	49.2	49.2
50°C	85	10.49	70.3
20°C		1.99	14.7
85°C	INERT		
85°	NaCl		



Z.D. Harris & J.T. Burns, "The effect of loading rate on the EAC behavior of AA7075-T651 in aqueous NaCl Soln", Corr & Mat Deg. 2, (2021) p360-375.





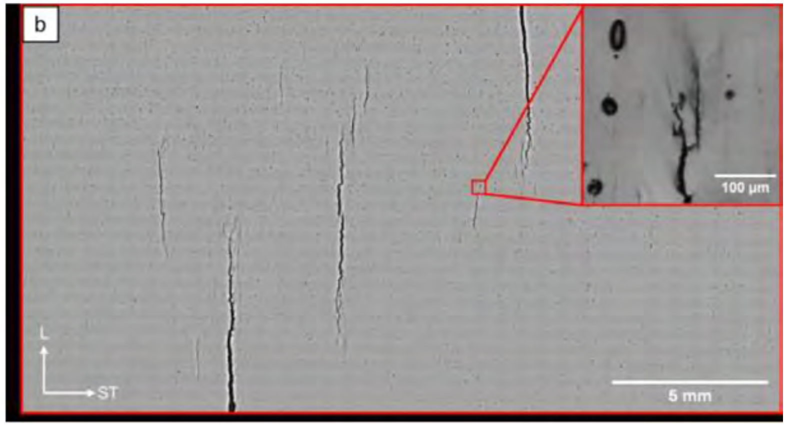
AFRL Supported Research on Unexpected EAC

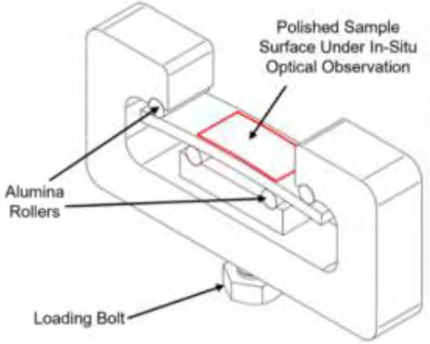
Dr. Henry Holroyd

Explore efficacy of stress intensity threshold values.

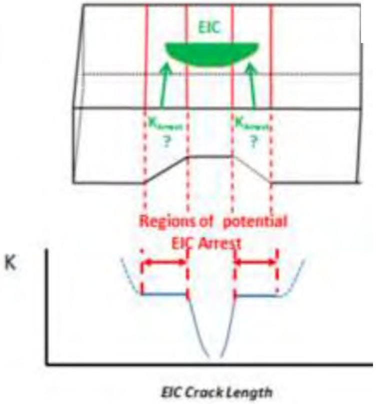
“Susceptible” *7085-T7452*
“Non-susceptible” *7050-T7451*

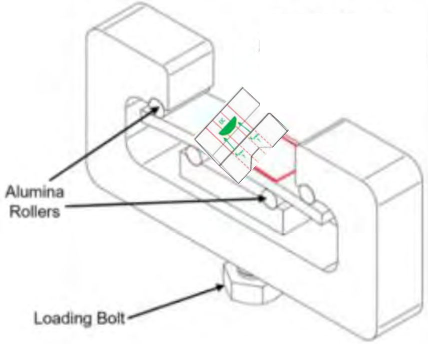
40°C	DRY	85	Primary Creep Exhaust (50/70%)
70°C	DRY	85	Primary Creep Exhaust (50/70%)
70°C	50	85	Crack Arrest





Initiation





Arrest

R.T. Euesden, et al., “In-Situ observation of EAC initiation and short crack growth behavior of new-generation 7xxx series alloys in humid air”, Corr Sci 216, (2023) 11051.

Federal Aviation Administration

FAA Opening Remarks

Presented at:

AFRL-FAA TIM on EAC / SCC of High Strength Al Alloys

November 5, 2024

Dayton, OH

Presented by:

Michael Gorelik, PhD

Chief Scientist for Fatigue and Damage Tolerance
Federal Aviation Administration

Problem Statement

- **Premature cracking of certain high-strength 7000-series Al alloys used in aircraft structures**
  - **Lacking apparent correlation to time in-service (FC / FH)**
  - **Demonstrates attributes of EAC / SCC**
  - **Potential contributing factors: alloy chemistry, humidity, temperature, stress**
    - **Stress – *several interpretations* → *mission profile*: cyclic vs. static; *residual stress* – mfg process; *assembly stress* – in-spec vs. out of spec**
- **Three areas of consideration:**
  - **Management of current fleet / COS**
  - **On-going production of previously certified aircraft models**
  - **Future TC / PC – material selection / screening / Qual&Cert**
    - *TC – Type Certificate; PC – Production Certificate (FAA)*
- **Products affected (*confirmed*) – Part 25 (multiple OEMs); Part 29 (select OEMs)**

Problem Statement (cont.)

- ***Potential*** **elements of path forward:**
  - **R&D – to address knowledge gaps (including potential coordinated multi-agency projects)**
  - **Consortium(s) or standards committee(s) – to share "lessons learned" and promote standardization**
  - **Agency-specific actions (e.g. policy statements, guidance materials); regulatory harmonization**
  - **More formal regulatory vehicles – ARC or ARAC (*need – TBD*)**

    ARC – Aviation Rulemaking Committee

    ARAC – Aviation Rulemaking Advisory Committee

Sample Questions to be Addressed

(not necessarily all during TIM)

- **Are we dealing with single or multiple mechanisms?**
- **What is the range of affected *Al* alloys?**
- **What material attributes make them susceptible?**
- **Do we understand the *physics* of degradation mechanisms?**
  - List of key contributing factors + rank-order
  - Can the onset and propagation of damage be *predicted or modeled*?
    - If yes – what are the gaps? If not – are “pass / fail” criteria the only option?
- **Can we develop robust Qual&Cert *test methods* and acceptance criteria that will safeguard against the degradation mechanisms in question?**
- **Is it feasible to eliminate the use of EAC-susceptible alloys going forward?**

Specific Expectations from TIM

- Identify community of practice and establish dialogue – *Day 1*
- Share technical information and "lessons learned" – *Day 1*
  - Understanding of pre-competitive "threshold" for information sharing across the industry
- Initial summary of knowledge gaps – *Days 1, 2*
- Initial definition of supporting / enabling R&D projects – *Day 2*
  - e.g. pipeline of project topics, prioritization, collaborative R&D opportunities
- Discussion of viable collaborative mechanisms going forward – *Day 2*
  - Government – industry – academia
  - Civil vs. military aviation
  - Part 25 only, or broader?
- Interactive discussion re. the Sample Questions on p. 4 via three parallel breakout sessions – *Day 2*

Discussion

Michael Gorelik, Ph.D., PMP

Federal Aviation Administration
Chief Scientist, *Fatigue and Damage Tolerance*
michael.gorelik@faa.gov

EAC

Certification & Continued Airworthiness

AFRL FAA Technical Interchange Meeting (TIM) on Environmentally Assisted Cracking (EAC) / Stress Corrosion Cracking (SCC) of High Strength 7000 Series Aluminum Alloys,

5 6 Nov 2024, Dayton OH

Simon Waite
Senior Expert – Materials EASA

Laurent Pinsard
Chief Expert - Airframe EASA

05.11.2024

Your safety is our mission.

An Agency of the European Union

Content

- EAC history
- Impact on certification
- EASA Corrective Action (SIB)
- Impact on Continued Airworthiness
- Conclusion & improvement for future certification
- Standard to be adapted

EAC History

Note: HEAC cracks typically not so obvious as 'typical' fatigue cracks – need for NDI inplace of visual for some ADs – see later

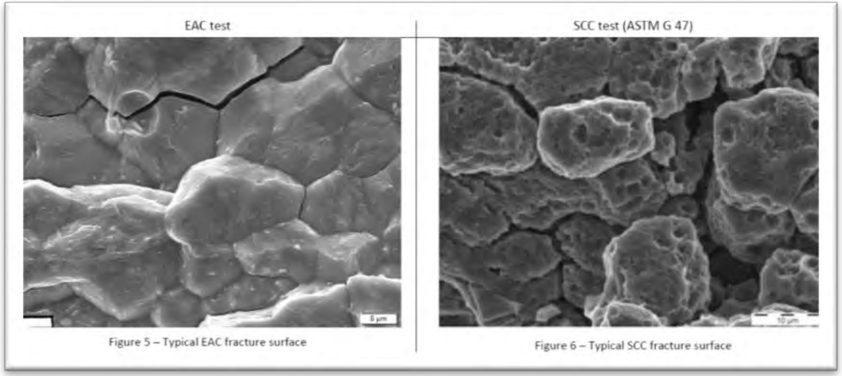
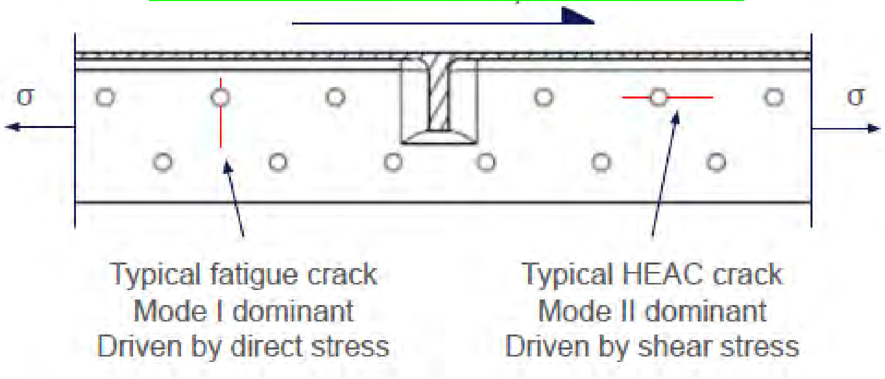


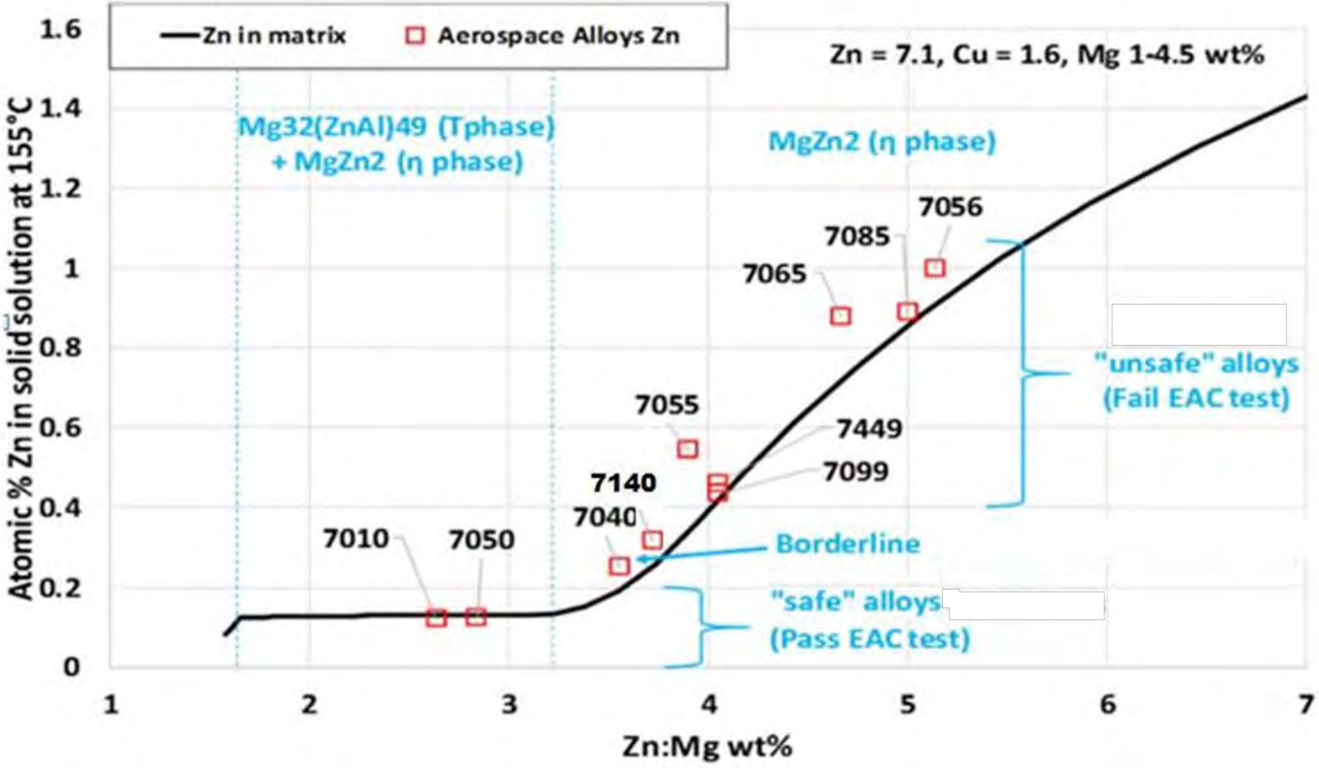
Figure 5 – Typical EAC fracture surface

Figure 6 – Typical SCC fracture surface



These cracks typically start from holes or other areas of stress concentration and usually propagate in a plane perpendicular to the short transverse (ST) direction. This phenomenon has been linked to the chemical composition of the alloy, notably a high zinc/magnesium ratio, combined with low copper content. Brittle fractures have been reproduced under laboratory environment and cracking has proven to be driven by time exposure (ageing) and is not fatigue related, although further crack propagation under operative loads cannot be excluded.

H-EAC History



EASA

H-EAC History

Susceptible alloy

Environment

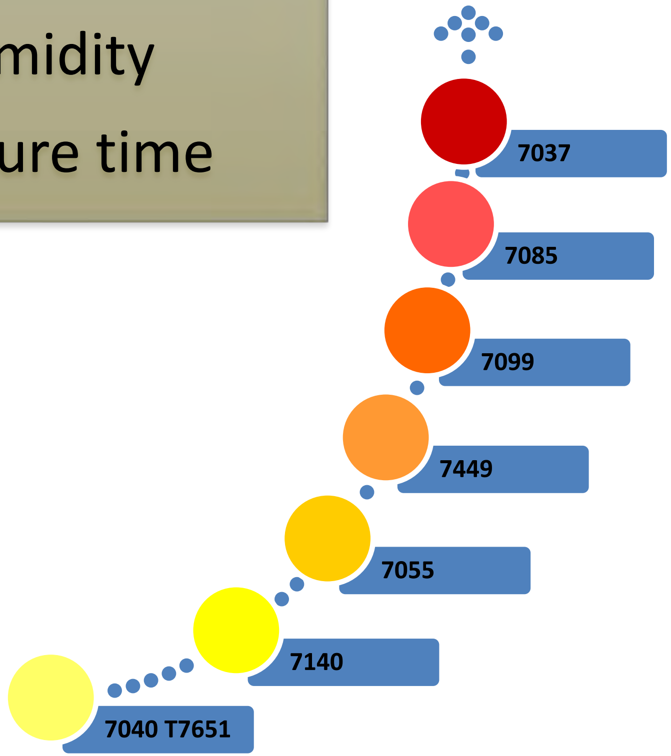
Humidity

Exposure time

EAC

3 factors

Stresses



H-EAC History

HYDROGEN ENVIRONMENT ASSISTED CRACKING OF AN AL-ZN-MG-(CU) ALLOY

George A. Young Jr. August 1999

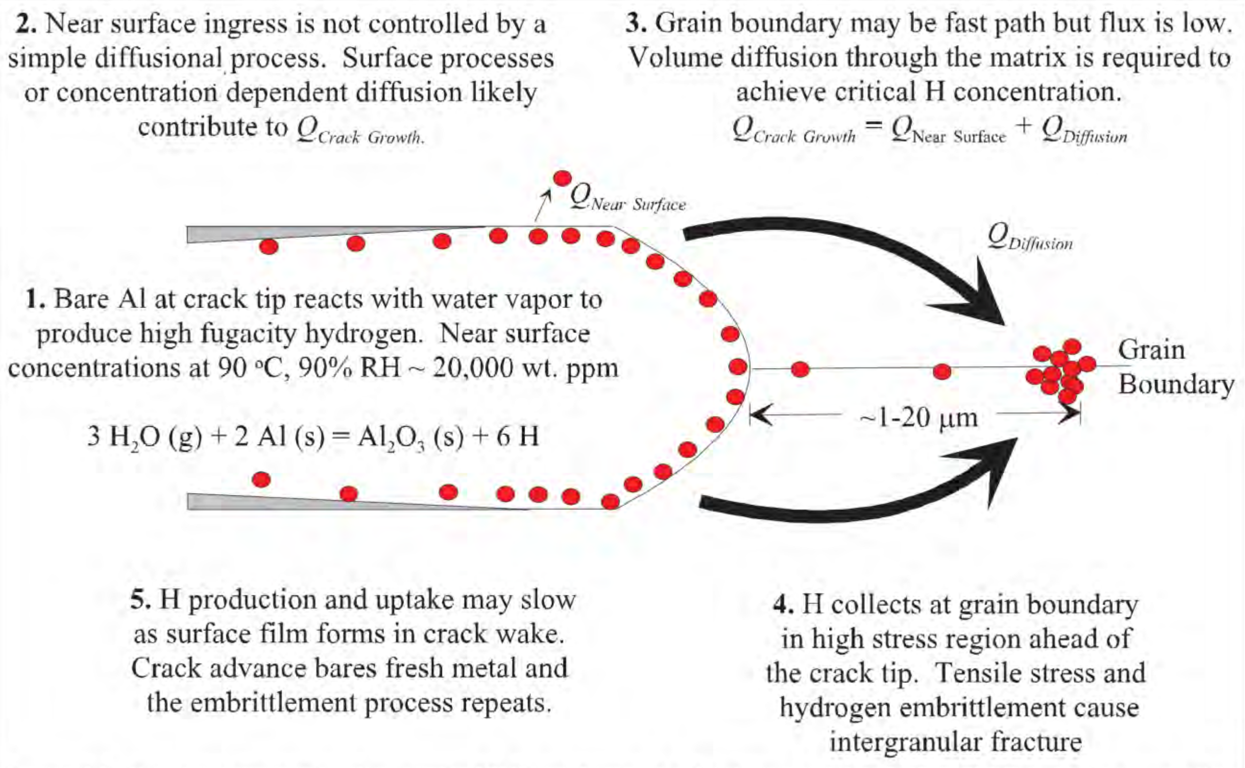


Figure 4.1. *Schematic illustration of a possible HEAC mechanism for the stage II crack growth of 7XXX series aluminum alloys exposed to humid air.*

A possible scenario for a link between environment and hydrogen embrittlement (without corrosion products)

EASA

EAC SIB

02440087.pdf

Awareness
- EASA SIB

Continued airworthiness
- Corrective action based on risk.
- Priority to PSE

Research
- Horizon 2020
- MMPDS update (TBC)

Safety Information Bulletin 2018-04

- **6 Aluminium Alloys are listed in EASA SIB :** 7037, 7040*, 7055, 7085, 7099, and 7449
- **EAC phenomenon can occur only when the three following conditions are present**: (1) susceptible material alloy, (2) sustained stress in the ST direction and (3) ageing in a typical environment
- **EASA recommends all affected organisations to evaluate the extent of the issue**, particularly to:
  - Identify components made of EAC sensitive aluminium alloys.
  - Evaluate the sensitivity to and criticality of EAC in the component.
  - Report these evaluation results to EASA.

Note: **SIB Revision 2018 04R2 March 2021**:
- added 7140 (T7651 temper)
- provides a 'generic' test method that can be used to support identification of material susceptibility to this form of EAC.

Military products

H-EAC SIB

‘Generic’ test method could benefit from common protocol to optimise identifying critical temperature, environment, load etc for any particular application and alloy

Appendix 1 – EAC Generic Test Method

1. EAC generic test method and test conditions:

As suggested by public literature or published test methods:

Specimen:

- Specimen geometry: Round smooth bar → according to ASTM G49 and ASTM E8 Tension test
- Align longitudinal axis of specimen (loading direction) with the Material ST grain direction

Loading:

- Loading device: Test rig → In Style of ASTM G49
- Loading: Constant load / displacement → according to ASTM G49
- Load level: set at 85% Yield only → In the style ASTM G64

Environment:

- Level of Humidity: 85% ± 5% → Ref. 1)
- Temperature: 70°C ± 1°C → Ref. 1)

Test time:

- Test duration is recommended to be at least 100 days

Example: Adapt SCC test in accordance with ASTM G 47

Experimental Conditions

- **Specimen** (typically): 60mm long round bar, dia. ~3mm
- **Load:** Constant 25-75 % Rp0.2
- **Environment:** **3,5% NaCl alternate immersion**
- **Temperature:** RT

EASA

H-EAC Experience & findings

- The intergranular fracture generated by H-EAC does not show any microscopic corrosion indication vs **S**tress **C**orrosion **C**racking (pitting visible in the grains)
- Interference fit (stress) and environmental conditions (moisture and temperature) are contributing factors to HEAC - not easily monitored or quantified.
- Crack initiation and propagation does not follow conventional laws currently used in F&DT evaluation.
- H-EAC characteristics are unpredictability & variability. Even if the parameters are now well identified, significant dispersion/scatter are observed in service: different parts installed on the same aircraft can be severely or barely affected.
- The "quality" or the detectability of the cracks is an additional issue to be considered for the H-EAC inspection: NDT requested

EAC findings

- Al 7085, 7075, 7449
- Perpendicular short transverse cracking combined with Interference fit
- Multiple cracks but parts randomly affected

Related ADs:

2019-0074: EC225 LP Main Rotor – Rotating Swashplate Yokes – Inspection / Rework / Service Life Limit

2019-0181R1: A350 Fuselage – Forward and Aft Cargo Door Latch Fitting External Lugs – Inspection / Modification

2021-0192: EC135B Main Rotor – Upper and Lower H legs – Service Life Limit

2022-0019: A380 Wings – Front and Rear Spars – Inspection

H-EAC Future Developments

- Alloy selection can be “controlled” (avoid EAC materials – high Zn/Mg ratio, low Cu etc)
- Improve understanding of crack growth - HEAC cracks are Mode II vs Mode I for conventional F&DT?
- Complex approaches like J-integral to capture the stability of the crack tip?
- Continue to inform industry of progress, identified product CAW actions in progress
- need to better standardise/improve test methods, e.g. to identify key parameter values:
  - Loads
  - Environment
  - Temperature

Thanks for your attention!

easa.europa.eu/connect

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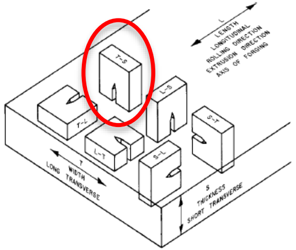
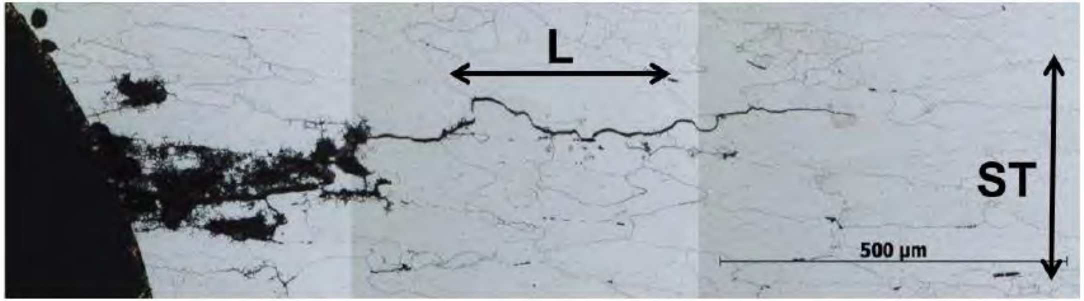
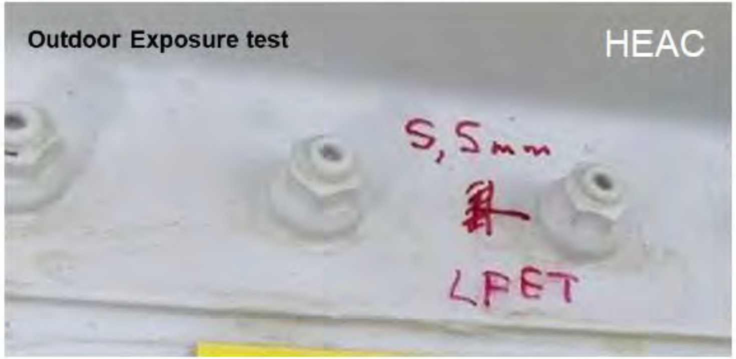
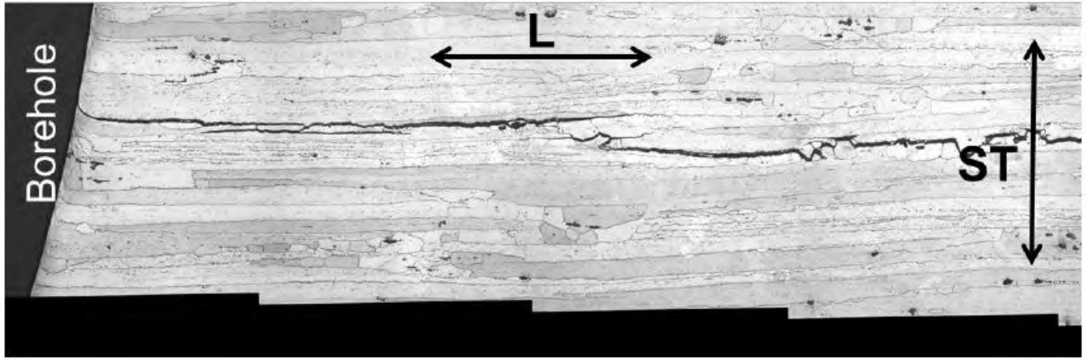
H-EAC History

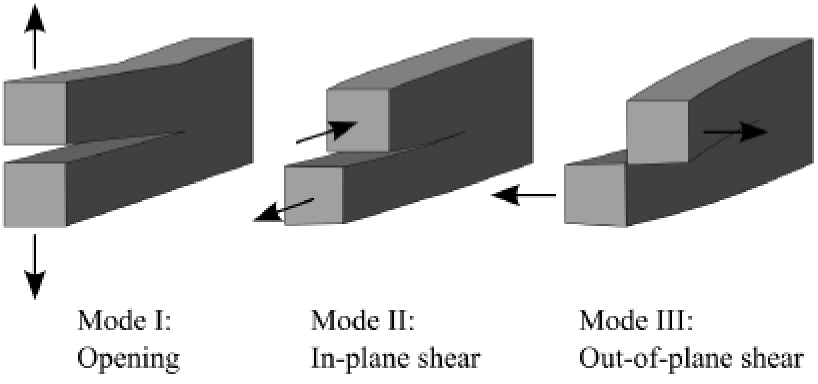


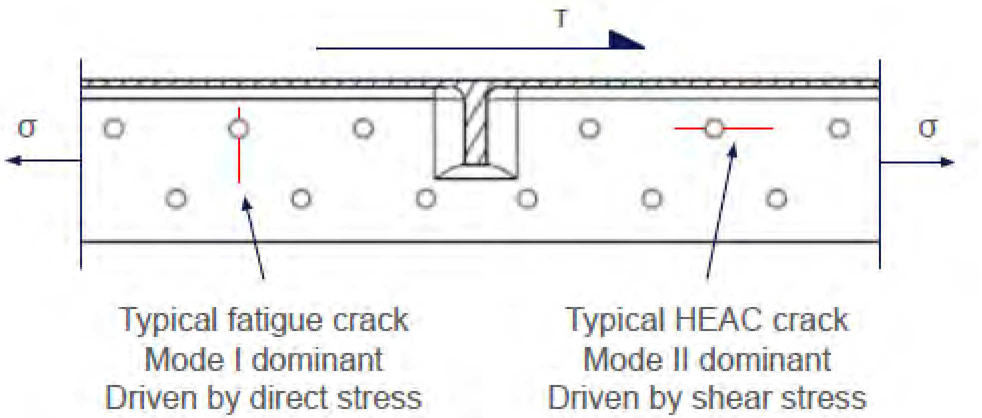






H-EAC History





For HEAC cracks, the location of initiation and growth results in cracks perpendicular to the normal fatigue crack direction and parallel to the primary bending stresses. For this reason, Mode 2 becomes thedominant crack mechanism.

H-EAC Qualification

SCC test in accordance with ASTM G 47

Experimental Conditions

- **Specimen** (typically): 60mm long round bar, dia. ~3mm
- **Load:** Constant 25-75 % Rp0.2
- **Environment:** **3,5% NaCl alternate immersion**
- **Temperature:** RT

HEAC

Experimental conditions to be adapted

- Loads
- Environment
- Temperature

Historical Overview of Environment-Induced Cracking of Al-Zn-Mg-Cu 7xxx series Aluminum Alloys

Henry Holroyd

5th November 2024

HH involvement with EIC of Aluminum Alloys

- **45+ years experience in Industry and Academia**
- **1979 First publication on Al-Zn-Mg-Cu EIC:**

“Reduced Ductility of a High Strength Aluminium Alloy During and After Exposure to Water“

- **For next 42 years we believed this an early report of pre-exposure embrittlement for a commercial Al-Zn-Mg-Cu alloy**
- **In 2020 I became aware of a 1913 study published in German.**

Several other unexpected findings during my deep-dive into
‘History of EIC in aluminum alloys’
(Covid-isolation in Southern Missouri in 2020/2021)

EIC in Commercial Aluminum Alloys started in 1899 (~125 years ago, 45 years earlier than previously thought)

Reasons why pre-1944 EIC incidents not previously captured are:

Alternate Descriptors:

- Spontaneous Disintegration
- Season Cracking of Aluminum
- Spannungskorrosion
- Intergranular fracture under prolonged application of Stress
- Acceleration of corrosion under stress
- Stress Cracking and

Failure to appreciate work published in German, French, Japanese …

1913 – Earliest EIC in Commercial Al-Zn-Mg-Cu Alloy during Structural Use

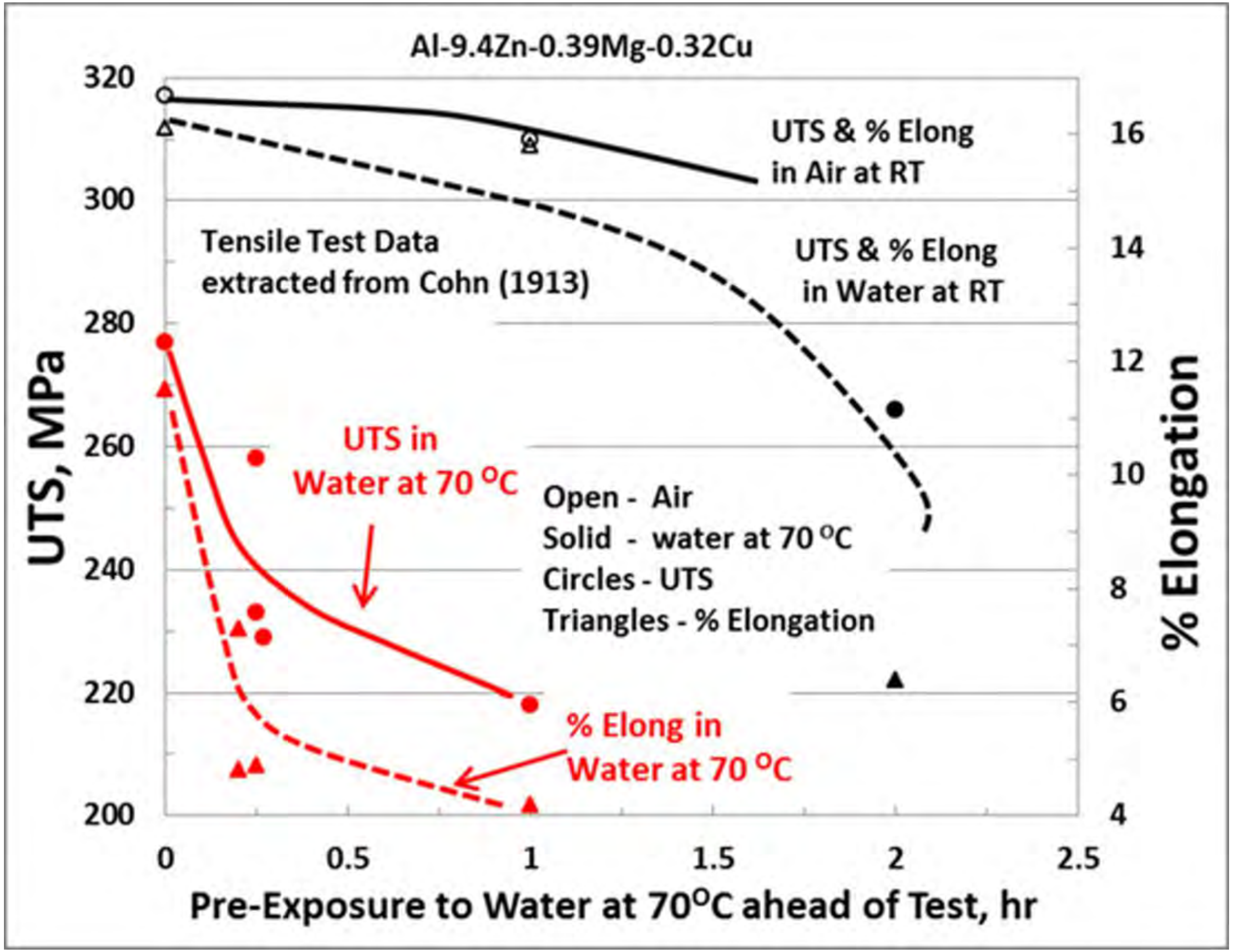
Al-9.4Zn-0.39Mg-0.32Cu (Zinc-Duralumin)

- Overhead Power Lines used Ore Mountain region of Germany

- Extrusions in German Zeppelin Airships bombing London in WWI

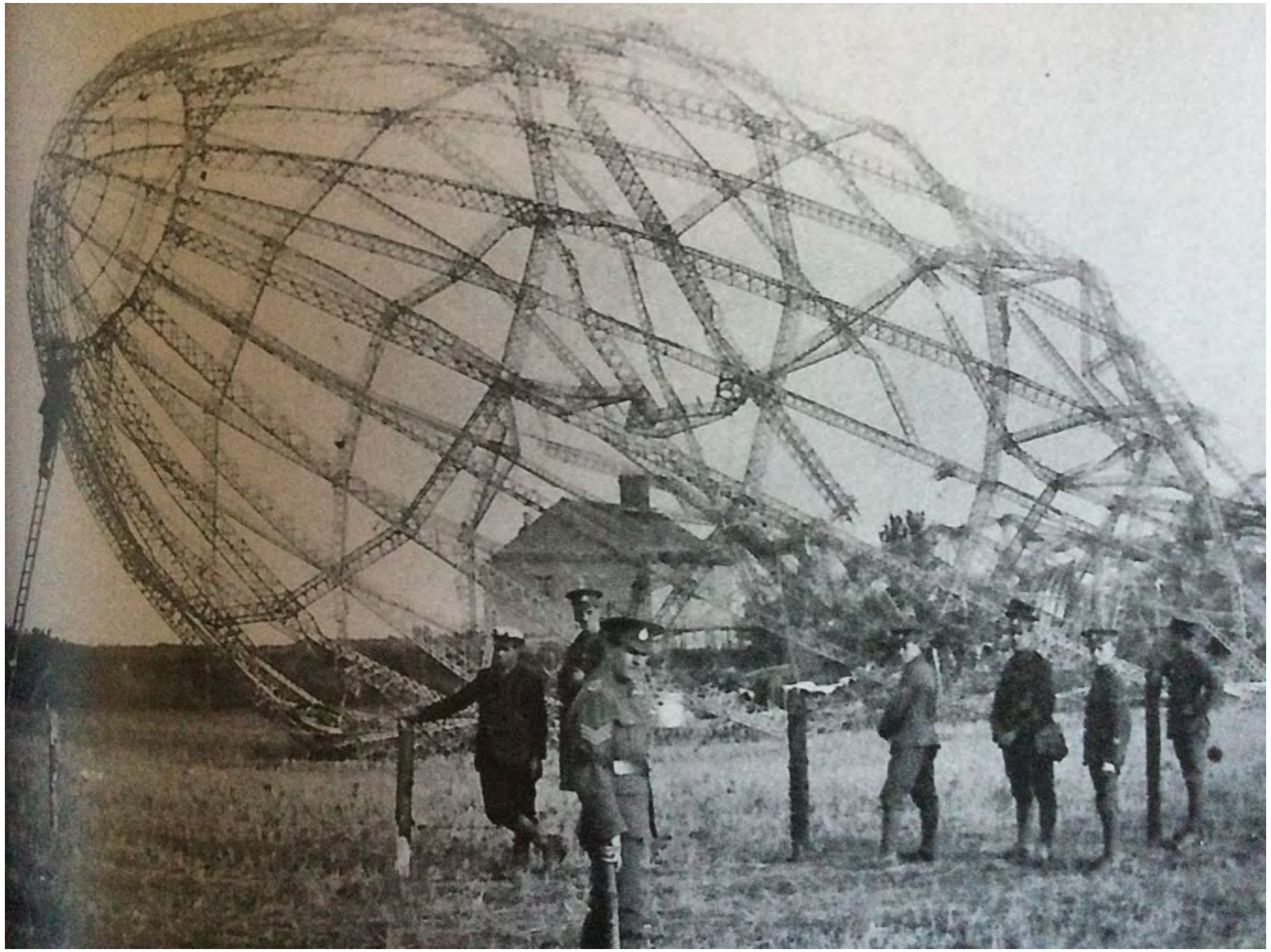
  (Japanese Naval Admiral 'purloined' sample from a Zeppelin downed by British in Croydon was sent to Japan via 'Diplomatic Bag')

Pre-exposure to water at 70°C and subsequent mechanical properties for Al-9.4Zn-0.39Mg-0.32Cu alloy tensile tested in air or water at RT and 70°C (1913)



Holroyd et al, Corrosion (2023)

London WW1 – Zeppelin Frame 1916



Early Al-Zn-Mg-Cu Alloy Development

- UK (NPL) 1919 initially active but later focus on other aluminum alloys
- Experimental alloys in US in late 1920's, efforts intensified during 1930's, stimulated by Military demand and UK's development of
  DTD 363 (Hiduminium RR77) at High-Duty Alloys in 1937
- Japanese studies lead to 'Extra Special Duralumin' (1936) used in Zero Fighter Planes (1938), subsequently exploited by US (1942) as basis for 75S, the precursor of AA7075

Materials Transactions, Vol. 64, No. 2 (2023) pp. 341 to 351
Special Issue on Aluminium and Its Alloys for Zero Carbon Society, ICAA 18

REVIEW

History of the Development of Extra Super Duralumin and Future Research Issues of Al–Zn–Mg Alloys

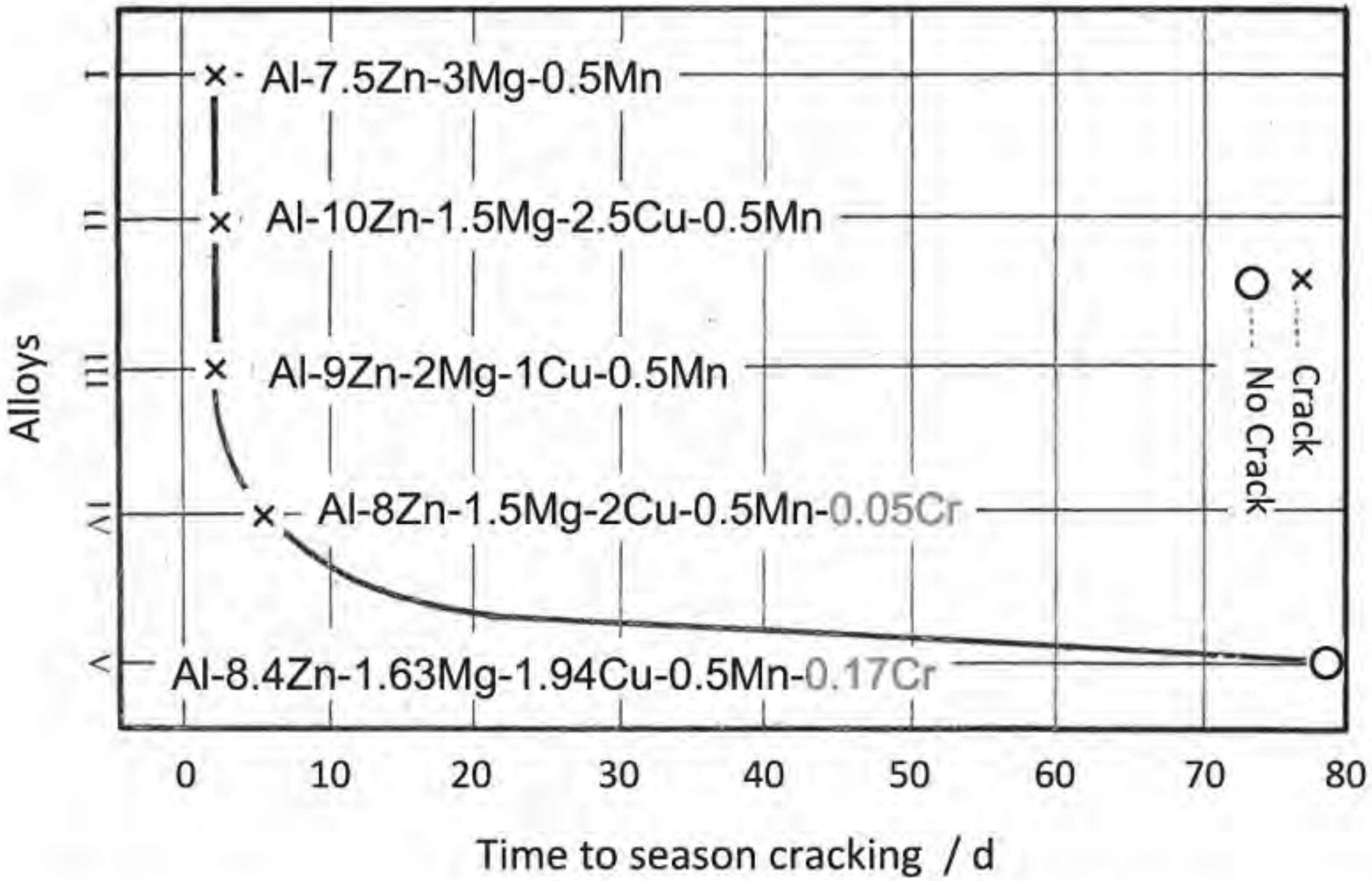
Hideo Yoshida*

ESD Laboratory, Nagoya 466-0005, Japan

Almost 85 years have passed since the development of Al–Zn–Mg–Cu Extra Super Duralumin in Japan in 1936. This alloy was developed by Dr. Igarashi in response to the Japanese Navy's order to Sumitomo to develop an alloy with tensile strength of 588 MPa (60 kg/mm^2) or higher, exceeding Alcoa's super duralumin 24S. This alloy was then adopted for use in the Zero fighter. Based on this alloy, Alcoa's 75S was developed in 1943. This paper describes the history of the development of Extra Super Duralumin, starting with Duralumin. The paper also discusses the issues that are considered important for the future development of the aluminum alloys based on the historical review and our study. One is the relationship between quench sensitivity and age-hardening properties of Al–Zn–Mg alloys and the second is the occurrence of shear fracture in the Al–Zn–Mg–(Cu)–Zr alloys. This is the points to be noted in the development of high strength and high toughness Al–Zn–Mg–Cu alloys. [doi:10.2320/matertrans.MT-LA2022019]

(Received May 30, 2022; Accepted July 21, 2022; Published January 25, 2023)

Keywords: *Duralumin, Extra Super Duralumin, 2024, 7075, stress corrosion cracking, quench sensitivity, shear fracture*



Effect of Cr addition on season cracking (SCC) of Al–Zn–Mg–(Cu) alloys.

I. Igarashi: Doctoral Thesis, Osaka Imperial University, (1939)

1930's to mid-1940's

Al-Zn-Mg-Cu Alloy development ongoing independently in US, UK, Germany and Japan

Alloy #	Year	Zn	Mg	Cu	Mn	Cr	UTS (MPa)	YS (MPa)	% Elong	Envisaged Product*
X70S (US)	1931	10.0	0.4	1.0	0.7	--	400	310	18	F
X71S US)	1932	10.0	2.0	2.0	1.0	--	585	560	10	S, E
XB71S (US)	1932	9.0	2.7	2.0	1.0	--	595	565	10	S
X73S (US)	1935	5.2	0.9	0.5	--	--	370	290	20	F
DTD 363A (UK)	1937	5.5	2.8	1.3	0.7	0.5	586	510	5	F, E
ESD (Japan)	1937	8.0	1.5	2.0	0.5	0.2	585	--	15	E, S
ESD (Japan)	**1939**	**6-8**	**1.2-1.8**	**1.5-2.5**	**0.3-1**	**0.1-0.4**				**E, S**
X7C70S (US)	1938	8.0	1.1	0.5	0.8	--	480	420	17	F
X74S (US)	1939	5.2	2.1	1.5	0.4	--	510	440	12	S
FLW 3415 (Germany)	**1942**	**4.5-5.5**	**2.0-2.8**	**0.5**	**0.2-0.3**	**0.2**	**451**	**354**	**3.8**	**S, E, W**
DTD 683 (RR77) (UK)	1943	UK	5.2-6.2	2.2-3.20	0.3-0.7	0.18-0.7	541	463	7	S, F, E
75S (US)	1943	5.6	2.5	1.6	--	0.25	570	500	11	S, P, F, E

***F = Forging, S = Sheet, P = Plate, E = Extrusion**

(1942- US access to Japanese ESD alloy from WW2 Zero Fighter Aircraft)

1950’s

Alloy #	Year		Zn	Mg	Cu	Mn	Cr	other	UTS	YS	% Elong	Product*
AA7178	1951	USA	6.3-7.3	2.4-3.1	1.6-2.4	0.3	0.18-0.28		600	540	10	S, P, E
AA7075	**1954**	**USA**	**5.1-6.1**	**2.1-2.9**	**1.2-2.0**	**0.3**	**0.18-0.4**		**570**	**500**	**11**	**S, P, F, E**
AA7079	**1954§**	**USA**	**3.8-4.8**	**2.9 - 3.7**	**0.4 -0.8**	**0.1-0.3**	**0.10-0.25**		**540**	**470**	**14**	**S, P, F, E**
AA7001	1955	USA	6.8-8.0	2.6-3.4	1.6-2.6	0.2	0.18-0.35		675	625	9	E
AZ74	1958	Germany	5.5-6.5	2.1-2.5	0.7-1.0	<0.1	0.15-0.25	0.3-0.5 Ag	590	539	9.8	F, P, E
X7080-T7	1965	USA	5.0-7.0	1.5-3.0	0.5-1.5	0.1-0.7	0.25		448	393	6	F
FLW 3415	1942	Germany	4.5-5.5	2.0-2.8	0.5	0.2-0.3	0.2		451	354	3.8	S, E, W
FLW 3425	1942	Germany	4.0-4.5	3-3.5	--	0.2-0.6	0.15-0.25			--	--	E

AA7075-T6 ---- AA7075-T73 ----AA7079-T6

- By 1950, 75S (AA7075-T6) was 20% of Alcoa's total shipment of heat-treatable aircraft products.

- EIC in thicker material (ST loading direction) forced increased use of overaged duplex –T73 temper along with its associated ~15 % strength loss.

- In 1954 Alcoa introduced a '<u>promising</u>' New Alloy AA7079-T6, believed then to provide:

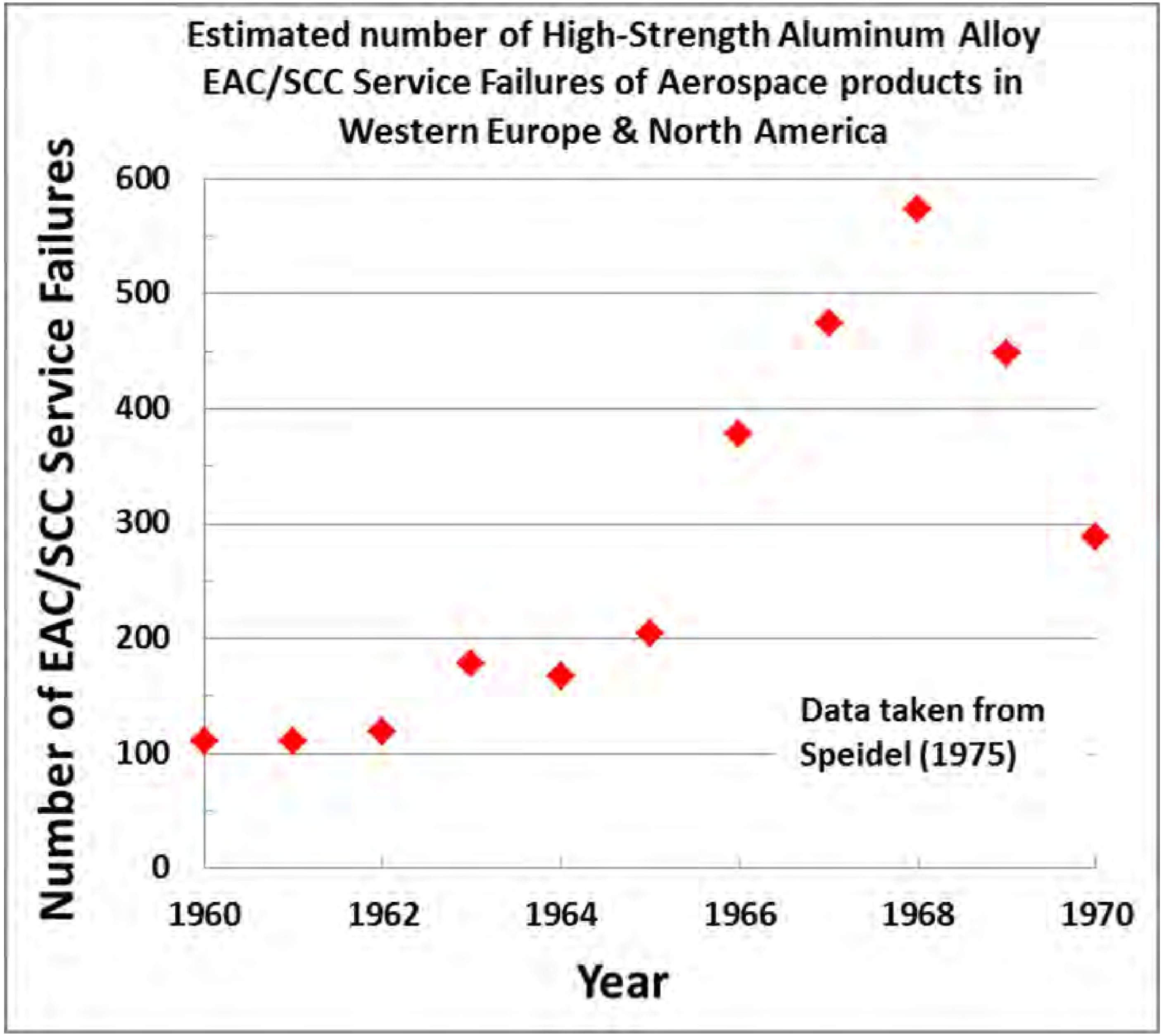
➢ Higher short-transverse ductility and mechanical strength properties in thick-sections than any other commercial aluminum alloy

➢ Improve EIC resistance relative to AA7075-T6, with cracking rarely initiating at stresses below 138 MPa during alternate immersion testing.

- AA7079-T6 usage grew rapidly during late 1950's to become in early 1960's the most used alloy for large high-strength forgings in the US

- EIC service issues during late 1950's, escalated to unprecedented levels during the 1960's

AA7079-T6 suffers EIC at ~ 50 MPa in Water Vapour (Duplex aging -T73 or RRA ineffective)



Estimated number of High-Strength Aluminum Alloy
EAC/SCC Service Failures of Aerospace products in
Western Europe & North America
Number of EAC/SCC Service Failures
600
500
400
300
200
100
0
1960
1962
1964
1966
1968
1970
Year
Data taken from
Speidel (1975)

Outfall of AA7079-T6 EIC Service Issues during the 1960's and early 1970's

Unprecedented R&D Funding from US Government Agencies flowed during the mid-1960's, through the 1970's into the early 1980's

Aspirational R&D Targets to address EIC performance included:

- **Full characterization of the cracking phenomena**
- **Provision of reliable accelerated EIC test methods**
- **Establishment of alloy chemical compositions and manufacturing process routes to provide adequate EIC resistance under expected service conditions**

US Government Agency R&D Funding (1963-1982) to characterize EIC/SCC of Aluminum alloys

Date	Tittle	Funding Agency	Recipient	Reports
May 1963 – May 1966	Investigations of the Stress Corrosion Cracking of High Strength Aluminum Alloys	NASA	Alcoa	Sprowls et al, 1966 [85]
Dec 1963 – Feb. 1966	Investigations of the Mechanisms of Stress Corrosion of Aluminum Alloys	Bureau of Naval Weapons	Alcoa	G C English 1965 [83] J McHardy 1966 [84]
1965 – 1966	A Fundamental Investigation of the Nature of Stress-Corrosion Cracking of Aluminum Alloys	American Air Force	Battelle Memorial Institute	F H Haynie et al 1967 [86]
1966 – 1968	Studies of Crack Initiation Phenomena associated with Stress Corrosion of Aluminum Alloys	NASA	Alcoa	M S Hunter et al 1966 [87] M S Hunter & W G Frickle 1969 [88]
March 1966 – March 1969	Development of a Rapid Stress-Corrosion Test for Aluminum Alloys	NASA	Kaiser Aluminum & Chemical Corporation	W J Helfrich 1968 [93]
June 1966 – June 1969	Studies of the General Mechanism of the Stress Corrosion of Aluminum Alloys and Development of Techniques for its detection	NASA	Tyco Laboratories, Inc	S B Brummer et al [91]
1966	Development of Higher Strength Aluminum Alloys with Improved Stress Corrosion Resistance	Air Force Materials Laboratory	The Boeing Company	J C McMillan, M V Hyatt [89]
May 1967 – May 1968	The Role of Dislocations in the Stress-Corrosion Cracking of Aluminum Alloys	Naval Air System Command	Rocketdyne, Rockwell Corporation	A J Jacobs 1968 [90]
1967 – 1969	Investigation to Improve the Stress-Corrosion Resistance of Aluminum Alloys through Alloy Additions and Specialized Heat Treatment	Naval Air System Command	Alcoa	J T Staley 1969 [92]
May 1967 – March 1970	Development of a High-Strength, Stress Corrosion Resistant Aluminum Alloy for use in Thick Sections	Air Force Materials Laboratory	The Boeing Company	J C McMillan, M V Hyatt, 1967 [88], 1968 [99] M V Hyatt, H W Schimmelbusch, 1970 [100]
July 1968- Aug. 1973	Evaluation of Stress-Corrosion Cracking Susceptibility using Fracture Mechanics Techniques	NASA	Alcoa	D O Sprowls et al 1973 [94]
July 1969 -Feb. 1972	Investigation of Smooth Specimen SCC Test Procedure. Variation in Environment, Specimen size, Stressing Frame, and Stress State.	NASA	Alcoa	B F Lifka, D O Sprowls, R A Kelsey [95]
May 1967 – March 1970	Development of a High-Strength, Stress Corrosion Resistant Aluminum Alloy for use in Thick Sections	Air Force Materials Laboratory	The Boeing Company	M V Hyatt, H W Schimmelbusch, 1970 [100]
July 1969 – July 1970	High Strength Aluminum Alloy Development	Air Force Materials Laboratory	Reynolds Metal Co.	D S Thompson, S A Levy, 1970 [101]

1970	Exploratory Development of High-Strength, Stress Corrosion Resistant Aluminum Alloy for use in Thick Section Applications	Air Force Materials Laboratory	Alcoa	J T Staley, H Y Hunsicker [107]
1970	Investigation to Develop a High-Strength Stress-Corrosion Resistant Aluminum Aircraft Alloy	Naval Air Systems Command	Alcoa	J T Staley [106]
1970	Investigation to Develop a High-Strength Stress-Corrosion Resistant Aircraft Alloy	Naval Air Systems Command	Alcoa	J T Staley [90EE]
Sept. 1970 – Feb. 1972	Further Development of Aluminum Alloy X7050	Naval Air Systems Command	Alcoa	J T Staley, J P Lyle, H Y Hunsicker, 1972 [105]
June 1971 – Dec. 1972	Comparison of Aluminum Alloy 7050, 7049, MA52, and 7175.T736 Die Forgings	Air Force Materials Laboratory	Alcoa	J T Staley, 1972 [9102]
May 1972 – Nov. 1974	Design Mechanical Properties, Fracture Toughness, Fatigue Properties, Exfoliation and Stress Corrosion of 7050 Sheet, Plate, Hand Forgings, Dia Forgings and Extrusions	Naval Air Command	Alcoa	RE Davies, G E Nordmark, J D Walsh, 1975 [103]
March 1973 – June 1976	Aluminum Alloy 7050 Extrusions	Air Force Materials Laboratory	Alcoa	J T Staley et al, 1977 [104]
1980	Seacoast Stress Corrosion Cracking of Aluminum Alloys	NASA	NASA	TS Humphries, E E Nelson, 1981 [196]
March 1981 – May 1982	A Study of Environmental Characterization of Conventional and Advanced Aluminum Alloys for Selection and Design Part 1: Literature Review Part 2: The Breaking-Load Test Method	NASA	Alcoa	D O Sprowls, 1984 [97] D O Sprowls et al, 1984 [98]

How successful was the R&D Investment?

- **Evolution and emergence of AA7050 and its multi-decade essentially EIC-free service performance is a major positive**

- **Progress on the EIC aspirational targets less impressive:**

- **Full characterization of the phenomena** **(Still only partially achieved)**

- **To provide reliable accelerated EIC test methods** **(Still awaiting major progress)**

- **Establishment of alloy chemical compositions and manufacturing process routes to provide adequate EIC resistance under expected service conditions** **(Alloy Development now limited by Zinc content Issue)**

Current Standard EIC Test Methods

2017 Russ Jones

ASM Book Stress Corrosion Cracking–Material Performance and Evaluation, 2nd Ed.

Chapter 17: Evaluation of Stress Corrosion Cracking

"One of the toughest problems for SCC investigators is that of convincing the decision makers that service life cannot be predicted in hard numbers because material traditionally have been evaluated by comparison"

HH et al (2024)

ASTM G47, G103, G129, G139 and G168 are unable to reliable differentiate between the EIC susceptibility of relatively resistant Al-Zn-Mg-Cu aluminum alloys.

Why are Today's EIC Tests Methods Inadequate?

- **EIC performances evaluated on the basis of comparison**
- **Environmental test conditions not relatable to expected 'Service Conditions'**
- **EIC initiation/early-stage growth rarely accessed, despite controlling EIC performance in structural applications**
- **Initial surface conditions non-relatable or representative of expected service use**
- **Complacency following AA7050 having no significant EIC Service Issues over decades**
- **Low-copper content Al-Zn-Mg-Cu alloys (AA7079, AA7039, AA7020) not the only a '<u>Special Case</u>'**
- **Failure to react to experimental evidence (e.g. Staley, 1973) Al-Zn-Mg-Cu alloys with higher-zinc contents than AA7050 have EIC propensities in natural atmospheres' undetected during standard ASTM G47 testing in alternate immersion saline solutions.**
- **ASTM G47, G103, G129, G139 and G168 testing fail to reliable differentiate between EIC susceptibility of relatively resistant Al-Zn-Mg-Cu aluminum alloys tempers**

Experienced–Based EIC Rating for Aluminum Alloys suggested by Sprowls et al (1973) using Smooth and Pre-Cracked Test Specimen Data

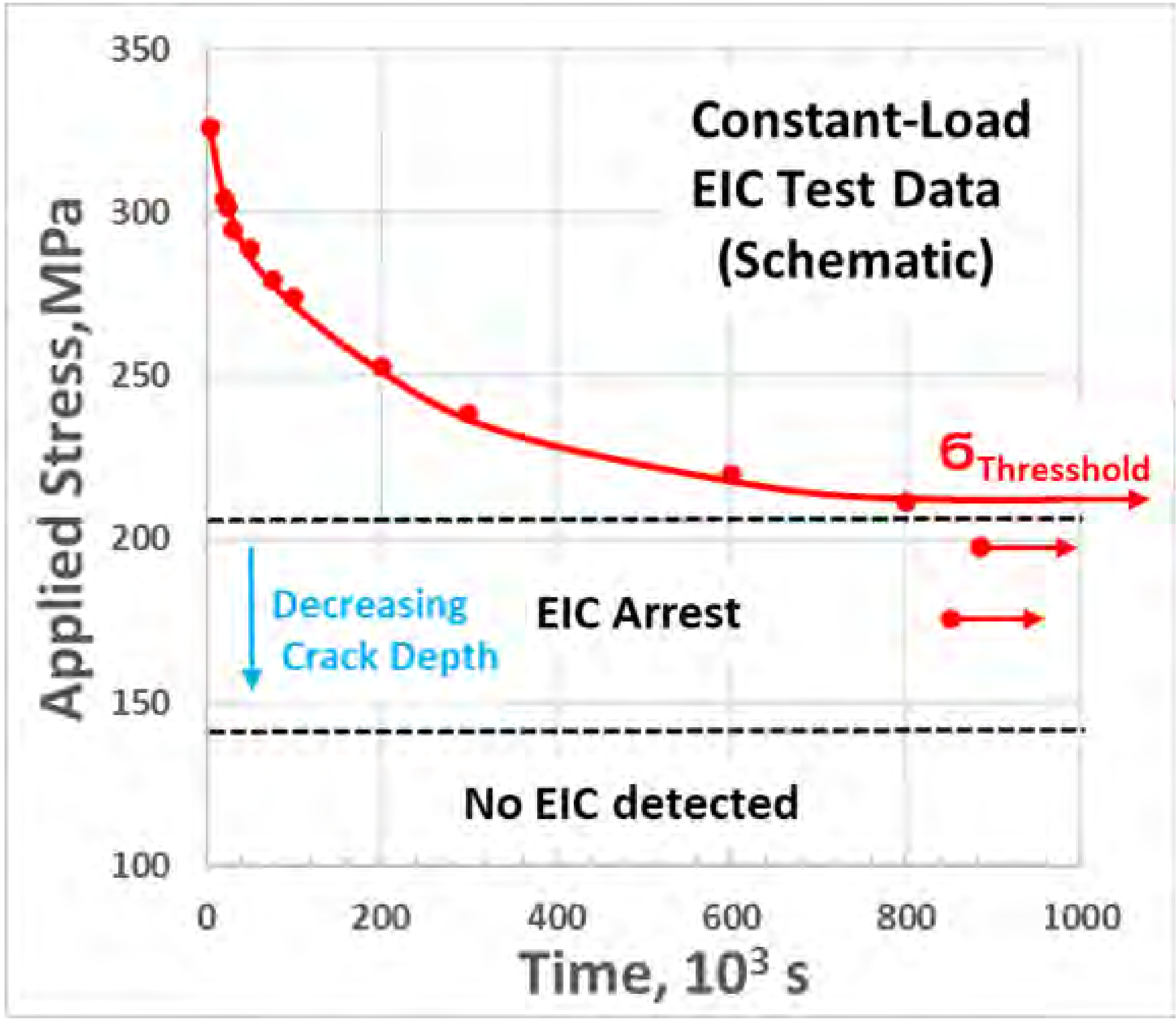
EIC Rating Susceptibility	EIC Threshold		EIC K-Insensitive Growth Rate (m/s)	Exfoliation Rating (ASTM G34)
	σ_{EIC} (MPa) % Yield Stress (ASTM G47)	K_{IEIC} % K_{IC} (DCB)		
A– Very Low	>90	>95	< 7×10^{-11}	P
B– Low	>75	>80	7×10^{-11} to 3×10^{-10}	P/EA
C–Moderate	>40	>50	3×10^{-10} to 3×10^{-9}	EA/EB
D-Appreciable	<40	<50	>3×10^{-9}	EB/EC

Experienced–Based EIC Rating for Aluminum Alloys suggested by Sprowls , et al (1973) using Smooth and Pre-Cracked Test Specimen Data

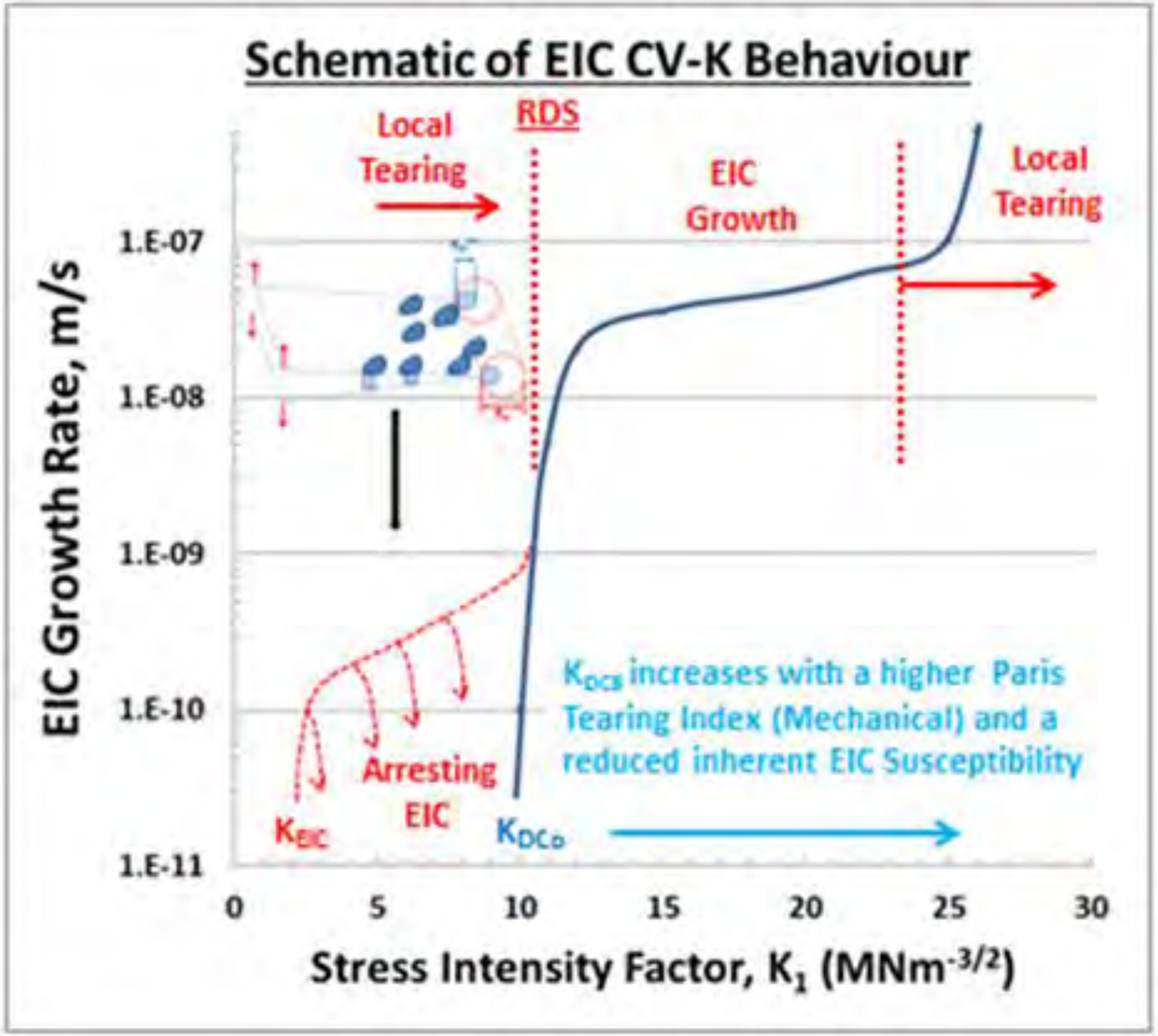
EIC Rating Susceptibility	EIC Threshold		EIC K-Insensitive Growth Rate (m/s)	Exfoliation Rating (ASTM G34)	**Typical Alloy**
	σ_{EIC} (MPa) % Yield Stress (ASTM G47)	K_{IEIC} % K_{IC} (DCB)			
A– Very Low	>90	>95	< 7×10^{-11}	P	**6061-T6**
B– Low	>75	>80	7×10^{-11} to 3×10^{-10}	P/EA	**7075-T73, 7050-T73**
C–Moderate	>40	>50	3×10^{-10} to 3×10^{-9}	EA/EB	**7075-T76, 7050-T76**
D-Appreciable	<40	<50	>3×10^{-9}	EB/EC	**7055-T77, 7085-T76**

Next Generation EIC Test Methods?

- Tests should be relatable to expected service conditions and focus on crack ‘initiation’, early-stage growth and crack ‘arrest’ behavior.



Holroyd et al., Corrosion (2023)



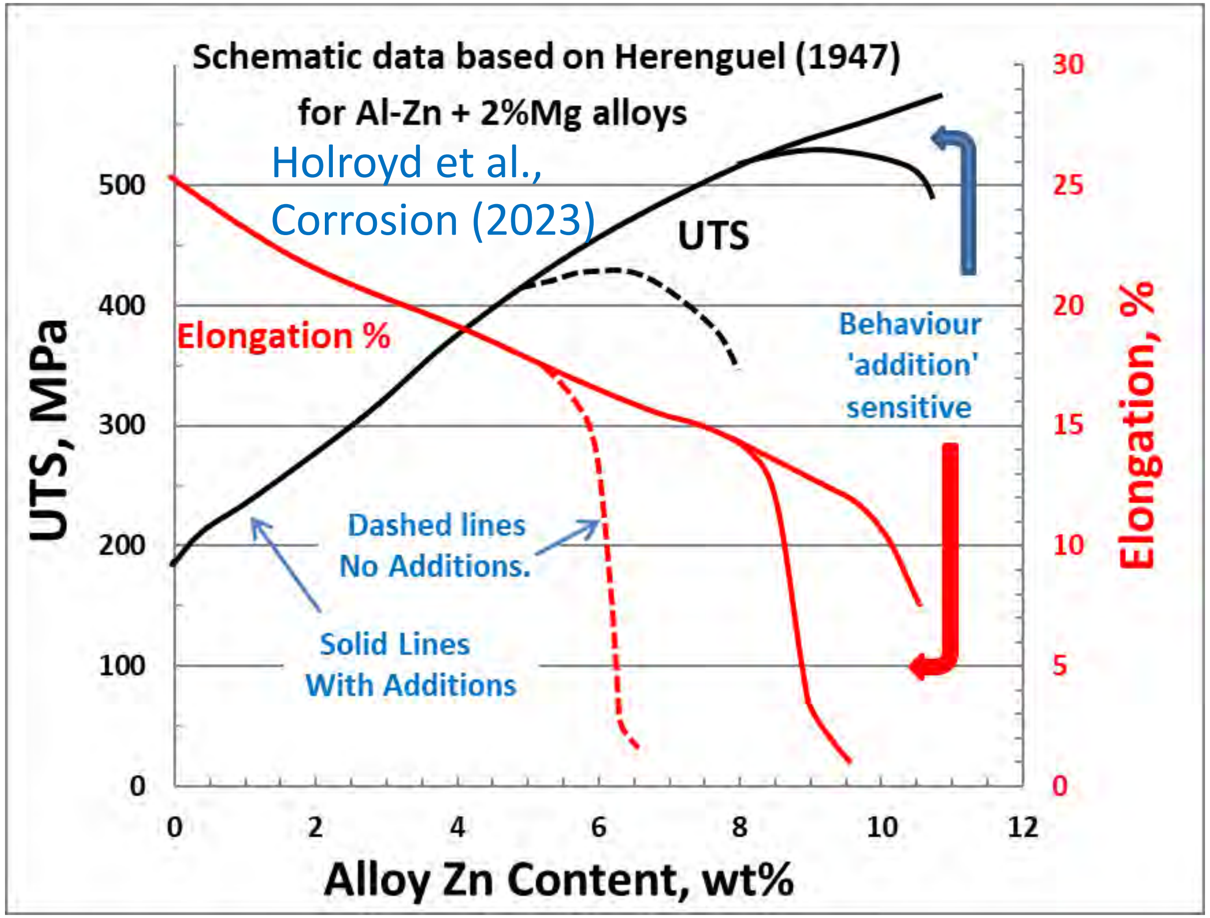
Holroyd et al., Corrosion (2023)

Al-Zn-Mg-Cu alloy Development
Next Generation?

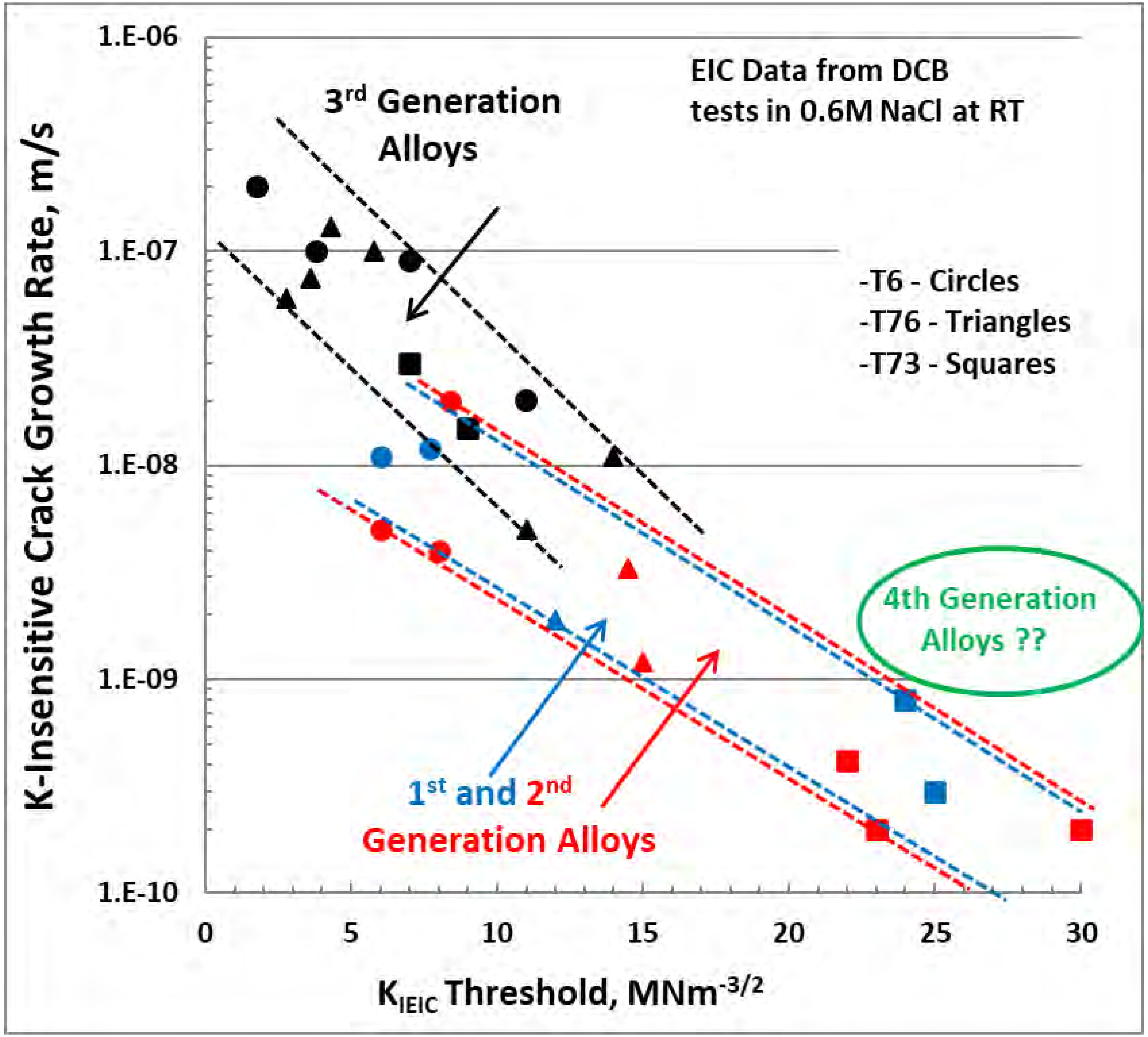
- Optimize current ‘Latest Generation’ Alloys first?

- Biggest Challenge is overcoming Maximum Zinc Content issue

Next generation Al-Zn-Mg-Cu Alloys will Require Understanding of Zinc Content Ceiling Issue



***Over-aging heat-treatments to reduce EIC becoming less effective with increasing Total Zinc content and non-existent for Zn > ~9 wt%**



Holroyd et al., Corrosion (2023)

History of Environment-Induced Cracking of Al-Zn-Mg-Cu 7xxx series Aluminum Alloys

Review Paper Published in January Issue of Corrosion (2023)

Environment-Induced Cracking of High-Strength Al-Zn-Mg-Cu Aluminum Alloys: Past, Present, and Future

(Henry Holroyd, Tim Burnett, John Lewandowski and Geoff Scamans)

(Is a 1960’s type EIC experience re-emerging?)

History of Aerospace Aluminum SCC Development and Testing

November 5, 2024

Ed Colvin

Chief Technical Officer - MELD Manufacturing

President & Consultant - HELM Technology, LLC

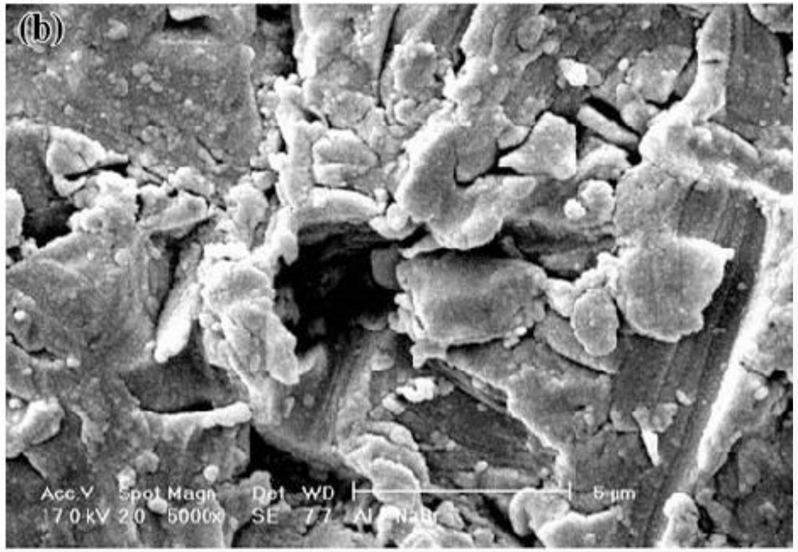
Retired VP Technology – Arconic/Howmet Aerospace

Aluminum Corrosion and EAC

There is no aluminum metal in nature, so eventually all the aluminum we have will corrode.

- **Inevitability** - The 2nd law of thermodynamics tells us that all aluminum metal will oxidize
- **Localized Corrosion** - Microstructural-mechanical-environmental interactions determine what part will corrode first and the resulting morphology
- **Timing** - Reaction kinetics, protection systems, and electrochemical factors tell us how fast
- **Consequences** – Structural design, service requirements, design life, etc. determine what matters.

In other words, it's all going to corrode, it's just a question of which part corrodes first, how fast, and what are the consequences?



Great People I’ve Been Fortunate Enough to Know Personally

During roles that included Corrosion Characterization, Corrosion & EAC Test Development, Alloy Development, Ingot Casting, Rolling, Extrusion & Forging Technology:

Don Sprowls

Mike Hyatt

Markus Speidel

Tom Summerson

Bernie Lifka

Basil Ponchel

Henry Holroyd

Jack Snodgrass

Jim Staley

Paul Ziman

John Liu

Bob Bucci

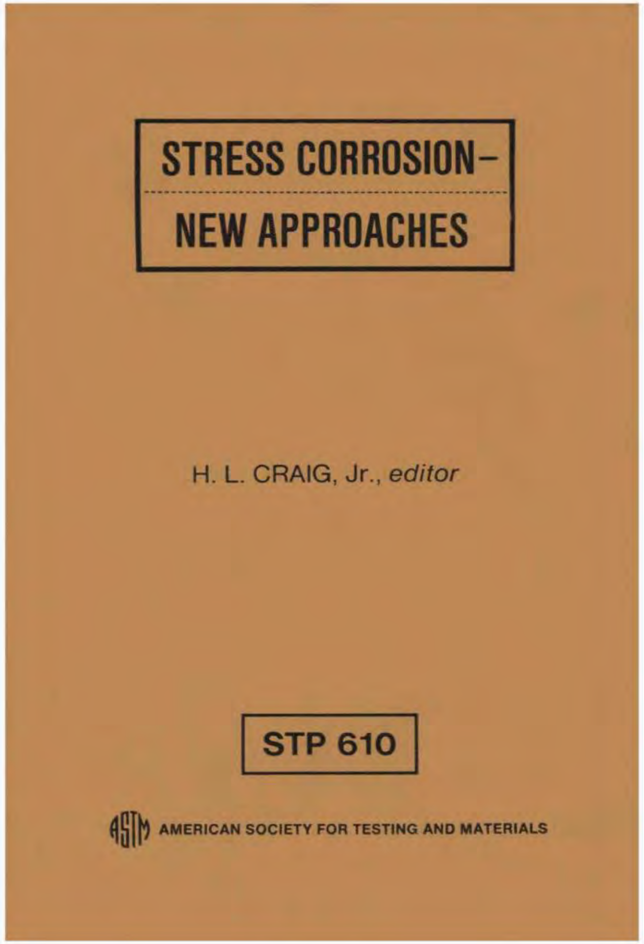
Glenn Stoner

Ed Starke

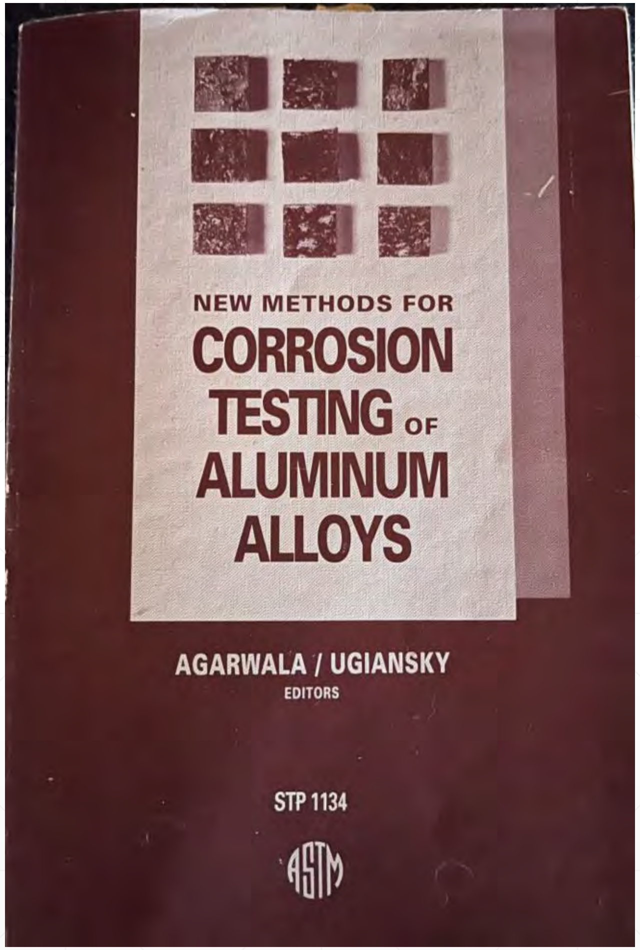
Howard Pickering

…plus many, many others

Two Key ASTM Special Technical Publications



Symposium
June 22-27, 1975
Montreal, Canada



Symposium
May 21-22, 1990
San Francisco, CA

2x24 & 7x75 Alloys – Thin Products that Became Thick

Table 3.2.3.0(a). Material Specifications for 2024 Aluminum Alloy

Specification	Form
AMS 4037	Bare sheet and plate
AMS 4035	Bare sheet and plate
AMS-QQ-A-250/4	Bare sheet and plate
AMS-QQ-A-250/5	Clad sheet and plate
AMS 4120	Bar and rod, rolled or cold-finished
AMS-QQ-A-225/6	Rolled or drawn bar, rod, and wire
AMS 4086	Tubing, hydraulic, seamless, drawn
AMS-WW-T-700/3	Tubing
AMS 4152	Extrusion
AMS 4164	Extrusion
AMS 4165	Extrusion
AMS-QQ-A-200/3	Extruded bar, rod, and shapes

Table 3.7.6.0(a). Material Specifications for 7075 Aluminum Alloy

Specification	Form
AMS 4044	Bare sheet and plate
AMS 4045	Bare sheet and plate
AMS 4078	Bare plate
AMS-QQ-A-250/12, 24	Bare sheet and plate
AMS-QQ-A-250/13, 25	Clad sheet and plate
AMS 4049	Clad sheet and plate
AMS 4122	Bar and rod, rolled or cold finished
AMS 4123	Bar and rod, rolled or cold finished
AMS 4124	Bar and rod, rolled or cold finished
AMS 4186	Bar and rod, rolled or cold finished
AMS 4187	Bar and rod, rolled or cold finished
AMS-QQ-A-225/9	Rolled or drawn bar and rod
AMS-QQ-A-200/11, 15	Extruded bar, rod, and shapes
AMS 4126	Forging
AMS 4141	Die forging
AMS 4147	Forging
AMS-A-22771	Forging
AMS-QQ-A-367	Forging

Both alloys were developed for thin sections in tempers intended for sheet and thin extrusions, 2024-T3X and 7075-T6X, which kept stresses in the L and LT directions, but still SCC was a key factor during development.

Aircraft developed in the 1950s required heavy section products making it possible to stress the ST direction and necessitating new test procedures.

Requirements for Large Scale Test Procedure

Capability to test thousands of specimens simultaneously.

Similar specimens and stress procedure to be used in natural and service environments

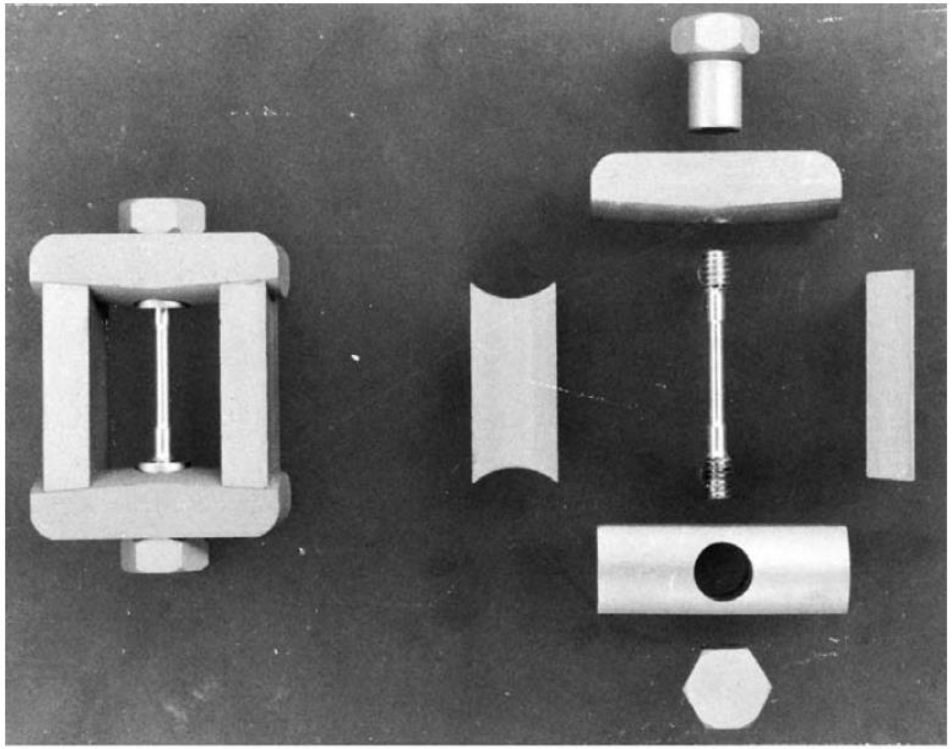
Test all grain orientations

One environment for as many alloy-temper combinations as possible

Objective failure criteria that can be used for development, qualification, quality assurance, and surveillance testing

Not intended to address specific crack growth mechanisms.

Non-requirement – perfect correlation with any specific service environment as there are an infinite number of service environments.



ASTM G47 – Alternate Immersion in 3.5% NaCl

Standard Test Method for Determining Susceptibility to Stress-Corrosion Cracking of 2XXX and 7XXX Aluminum Alloy Products[1]

This standard is issued under the fixed designation G47; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

Cyclic exposure to 3.5% NaCl in a controlled humidity to produce wet-dry cycles that mimic natural and service environments.

Small specimens emphasize crack initiation rather than crack growth.

Daily inspection for cracking.

Differentiation between cracking and IG corrosion.

Alternative solutions such as artificial seawater.

4. Significance and Use

4.1 The 3.5 % NaCl solution alternate immersion test provides a test environment for detecting materials that would be likely to be susceptible to SCC in natural outdoor environments, especially environments with marine influences.[3,4,5] For determining actual serviceability of a material, other stress-corrosion tests should be performed in the intended service environment under conditions relating to the end use, including protective measures.

13. Precision and Bias

13.2 *Bias*—The procedure in Test Method G47 has no bias because the result of the pass-fail stress-corrosion cracking test is defined only in terms of this test method.

Compromises Required for a Single Environment

G47 was intended for comparative rankings in a single environment that correlated with the seacoast.

- From the start they knew that 2xxx & 7xxx alloy relative life expectancies were not the same AI vs. seacoast.
- Industrial and acid environments produced different life expectancies.
- Alloy response within the 7xxx family varied, 7075 vs. 7079.

Stressing techniques based on thickness and need for long-term outdoor exposure.

- Window frame
- C-rings
- Sheet bend specimens

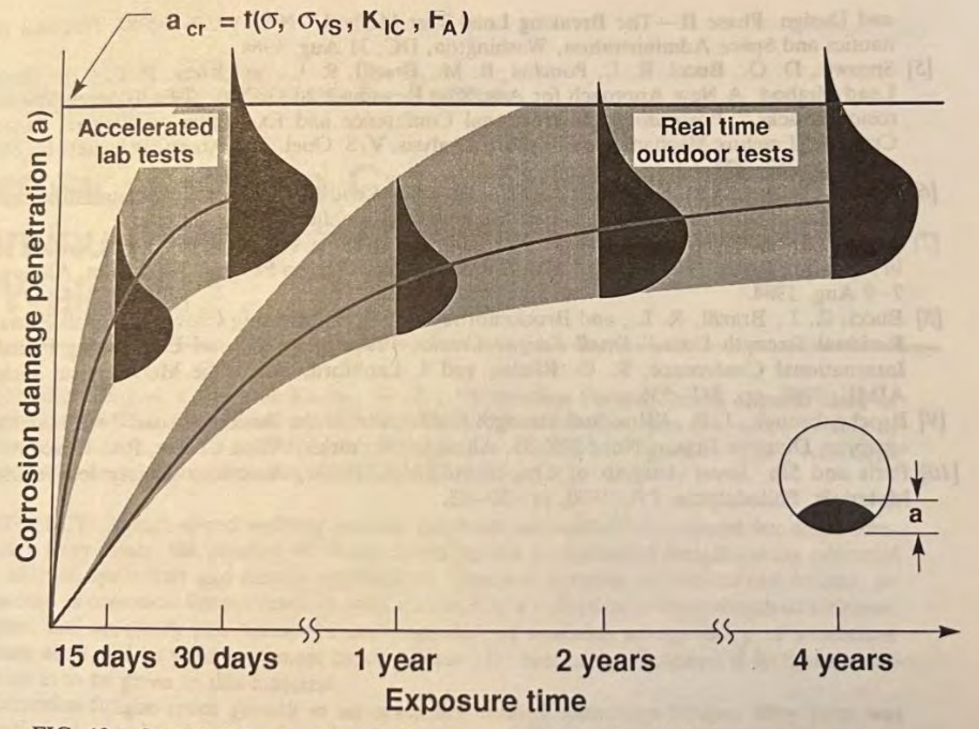


FIG. 12—*Statistical damage correlation in accelerated and real time corrosion tests.*

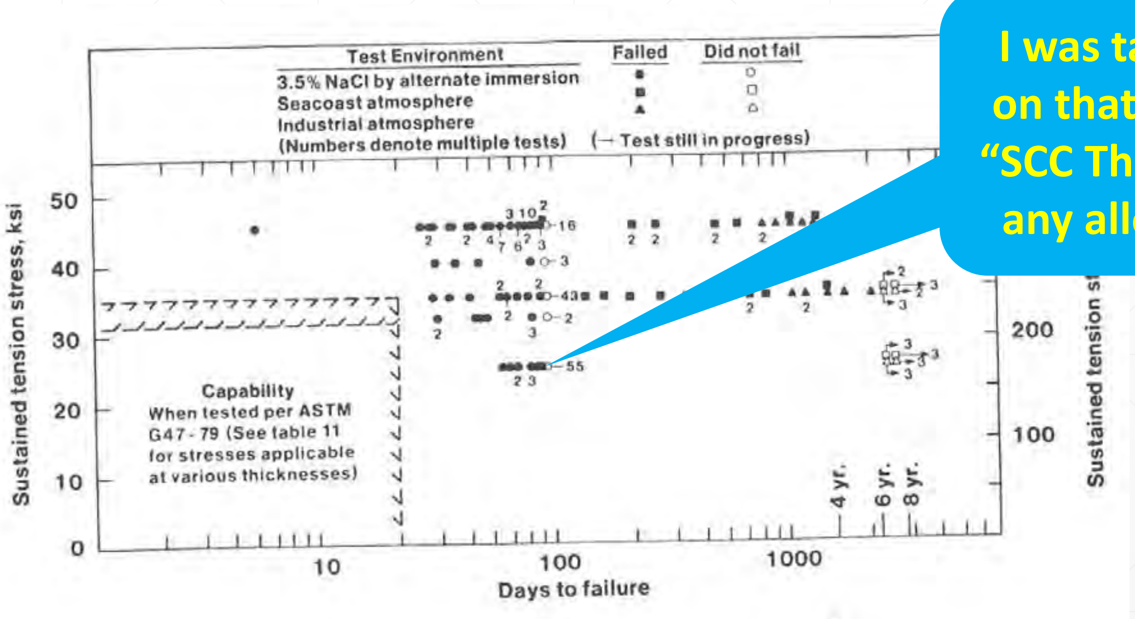
Learnings and Developments from Alloy 7050

The correlation between G47 and seacoast exposure was not the same for 2x24 and 7x75.

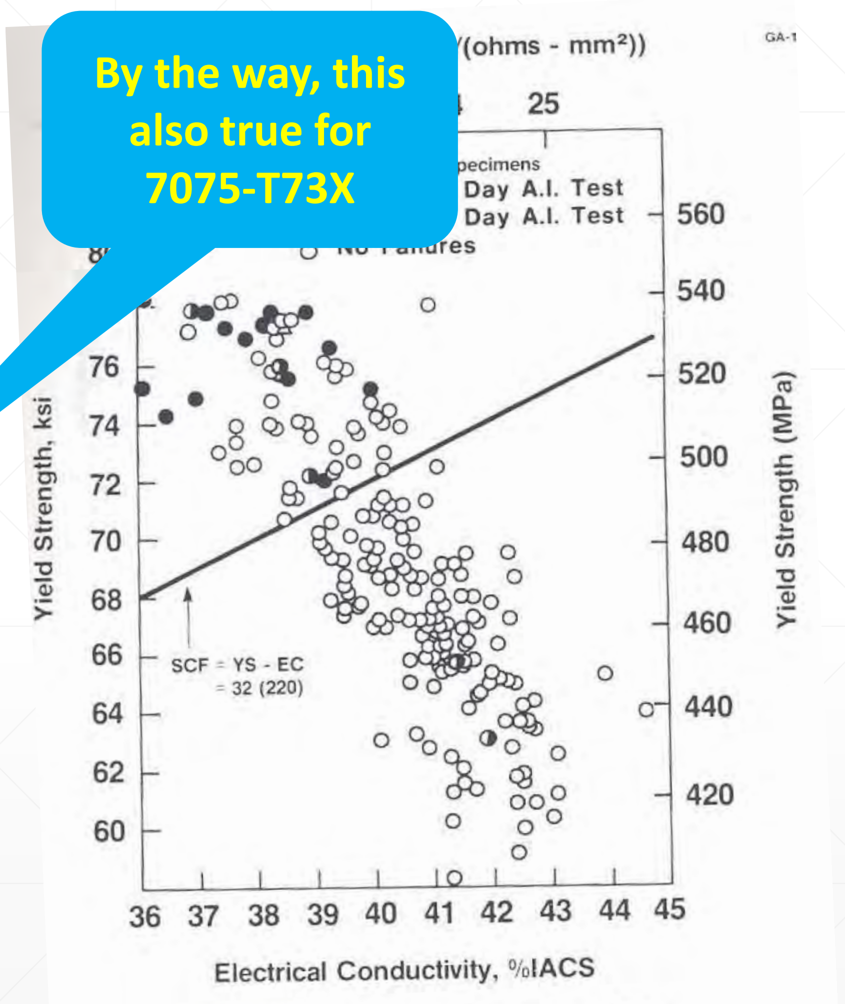
7050 showed a slightly different correlation than 7075.

Eventually 7050 will experience more failures severe seacoast locations than in G47.

Strength-conductivity relationship developed during the 7050 efforts.



Short-Transverse Stress-Corrosion Tests of
7050-T7451X Extruded Shapes 1.2-2.93 in. (30-74 mm) Thick



Proposed Stress Corrosion Factor, SCF,
(Sloping Line) Acceptance Criteria and
Summary of Stress Corrosion Performance of
7050-T7451 Plate Tested at 35 ksi (241 MPa)

Figure 10

By the way, this also true for 7075-T73X

I was taught early on that there is no "SCC Threshold" for any alloy-temper.

Resulting Ratings Based on G47 as Described in G64

TABLE 1 Practical Interpretation of Ratings for Resistance to SCC

NOTE 1—The stress levels mentioned below and the test stresses mentioned in 6.2 are not to be interpreted as "threshold" stresses, and are not recommended for design. Other documents, such as MIL-HANDBOOK-5, MIL-STD-1568, NASC SD-24, and MSFC-SPEC-522A, should be consulted for design recommendations.

Rating	Interpretation
A	Very high. SCC not anticipated in general applications if the total sustained tensile stress[A] is less than 75 % of the minimum specified yield strength for the alloy, heat treatment, product form, and orientation.
B	High. SCC not anticipated if the total sustained tensile stress[A] is less than 50 % of the minimum specified yield strength.
C	Intermediate. SCC not anticipated if the total sustained tensile stress[A] is less than 25 % of the minimum specified yield strength. This rating is designated for the short transverse direction in improved products used primarily for high resistance to exfoliation corrosion in relatively thin structures where appreciable short transverse stresses are unlikely.
D	Low. SCC failures have occurred in service or would be anticipated if there is any sustained tensile stress[A] in the designated test direction. This rating currently is designated only for the short transverse direction in certain materials.

[A] The sum of all stresses including those from service loads (applied), heat treatment, straightening, forming, and so forth.

Review of the rating tables immediately shows the importance of not just alloy, but also temper, product form, and stress direction.

Alloy and Temper[A]	Test Direction[B]	Rolled Plate	Rod and Bar[C]	Extruded Shapes	Forgings
7049-T76	L	[D]	[D]	A	[D]
	LT	[D]	[D]	A	[D]
	ST	[D]	[D]	C	[D]
7149-T73	L	[D]	[D]	A	A
	LT	[D]	[D]	A	A
	ST	[D]	[D]	B	A
7050-T74	L	A	[D]	A	A
	LT	A	[D]	A	A
	ST	B	[D]	B	B
7050-T76	L	A	A	A	[D]
	LT	A	B	A	[D]
	ST	C	B	C	[D]
7075-T6	L	A	A	A	A
	LT	B[E]	D	B[E]	B[E]
	ST	D	D	D	D
7075-T73	L	A	A	A	A
	LT	A	A	A	A
	ST	A	A	A	A

Rise of Precracked Specimens - 7075-T6X vs. 7079-T6X

7079-T6X showed more severe SCC in service than 7075-T6X, despite no more susceptibility in alternate immersion.

The seacoast did not differentiate the alloys properly either.

It took a long time, but eventually industrial environments, acid rain, showed a difference between the two alloys.

One key aspect was initiation time relative to crack growth rate.

DCB testing really shows the difference, 7079-T6X has much exhibits much faster crack growth rates in saline environments than 7075-T6X.

Notably the crack growth in saline environments is largely independent of exposure conditions.

G168 covers DCB testing.

Work by both Hyatt and later Lukasak, et al., shows that crack growth is a factor in smooth-specimen G47 time-to-failure, in fact, the Breaking Load method, G139, can show crack growth rates.

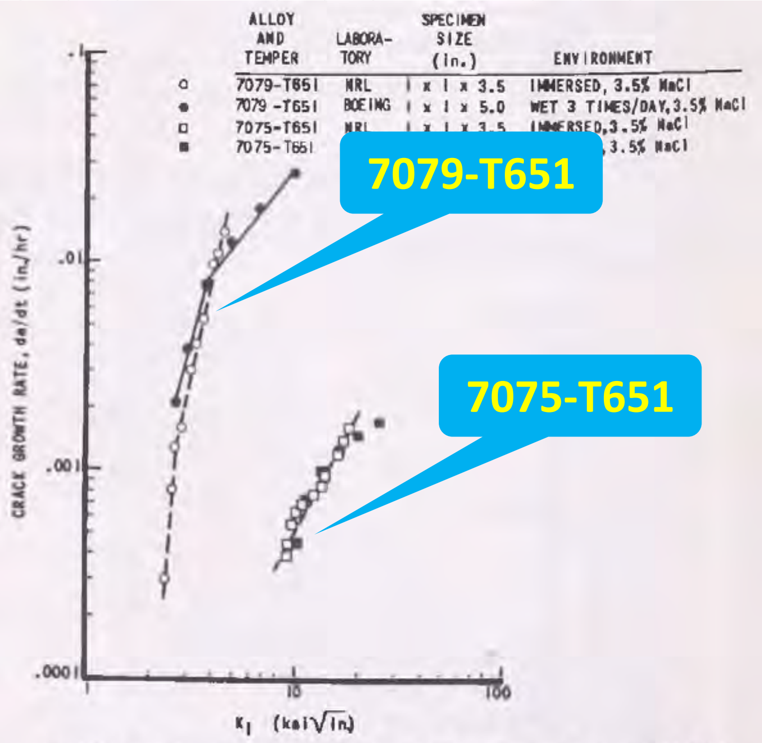


FIGURE 12 — K_I-rate data for DCB specimens tested at two laboratories. The 7079-T651 specimens were from the same piece of 1-inch thick plate, whereas the 7075-T651 specimens were from 1-inch thick plate from different heats.

(4) Hyatt, M. V., "Use of Precracked Specimens in Stress-Corrosion Testing of High Strength Aluminum Alloys," *Corrosion*, Vol 26, No. 11, November 1970, pp. 487-503.

Barriers to Change

There was a lot of corrosion test method development in the 1980s and 1990s, but minimal implementation.

Have to test thousands of specimens in numerous environments and compare to incumbent products.

Quality assurance tests have to be relatively quick and use limited material.

Existing specifications make any sort of change difficult even for new alloys.

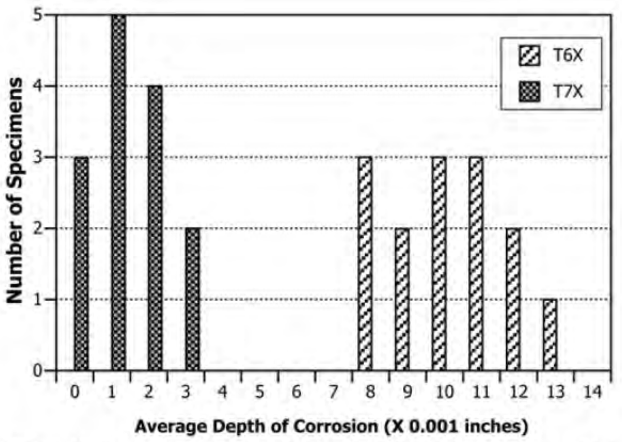
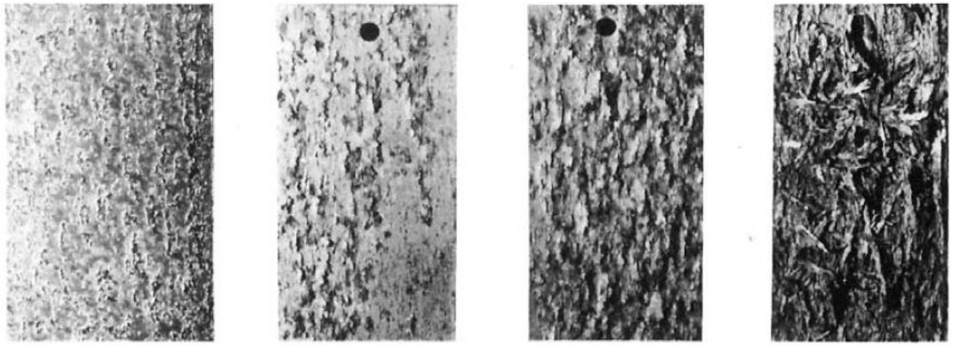


FIG. 8 Histogram of Average Corrosion Depths as Measured by Ultrasonic Inspection for Two Tempers of 7075 Plate at the T/4 Plane



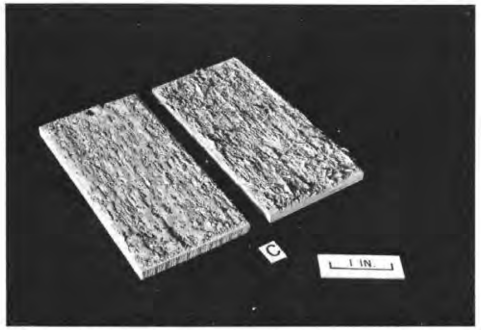
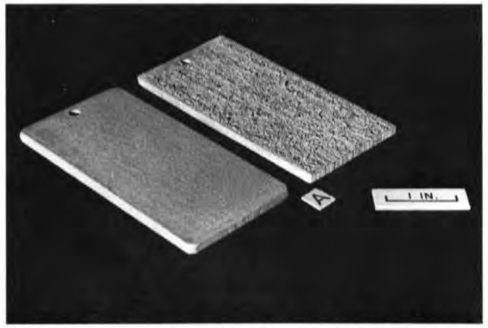


FIG. 5 Examples of Exfoliation Rating EC (Severe): Penetration to a Considerable Depth into the Metal



ples of Exfoliation Rating EA (Superficial): Tiny Blisters, Thin Slivers, Flakes or Powder, with only Slight Sepa Metal

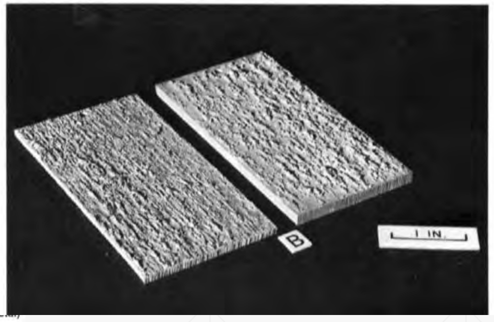
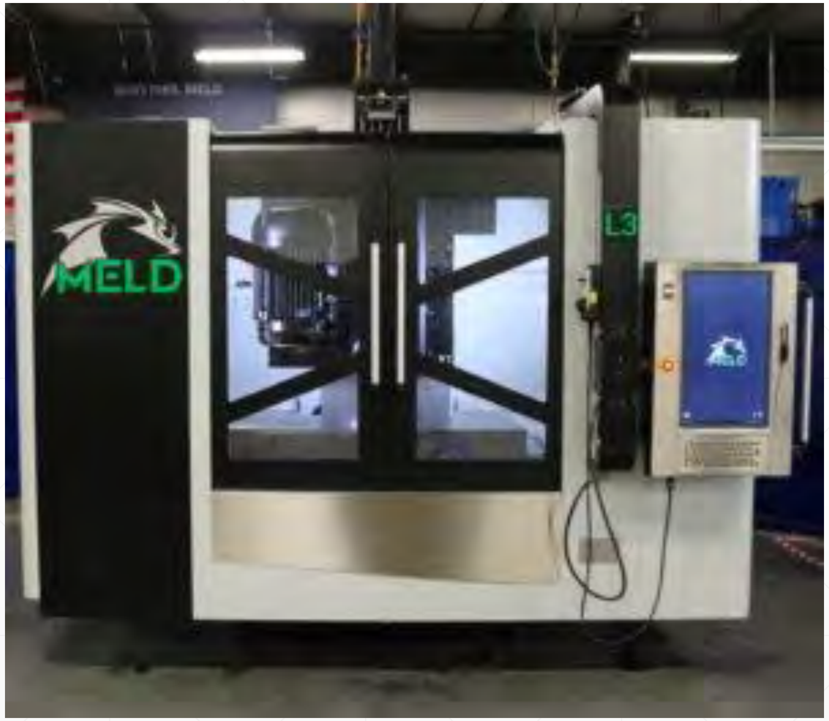
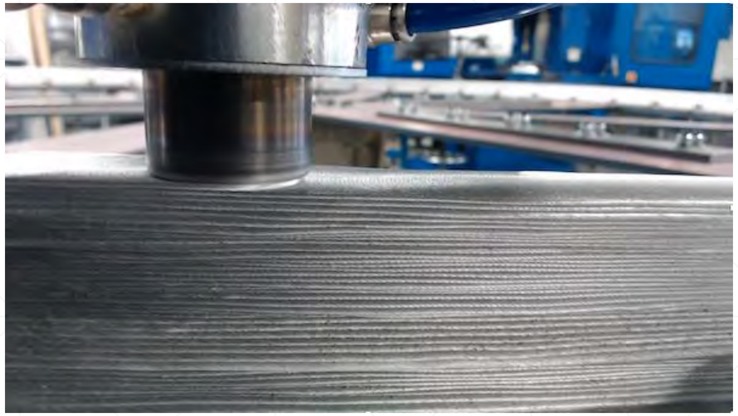
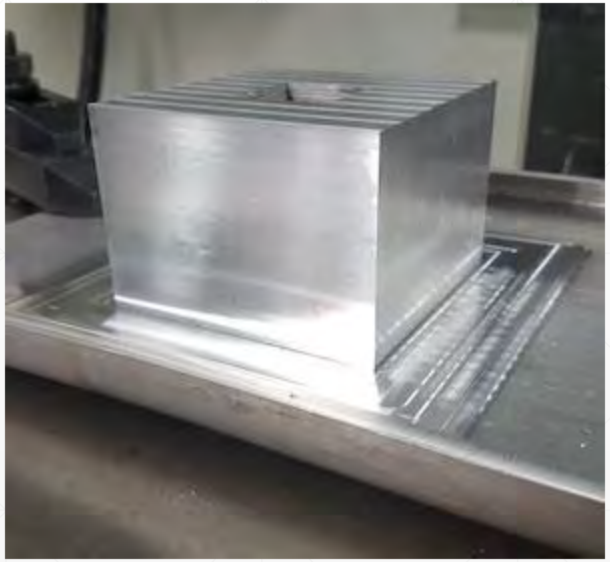


FIG. 6 Examples of Exfoliation Rating ED (Very Severe) (Similar to EC Except for Much Greater Penetration and Loss o

Current Role - MELD Manufacturing, Chief Technical Officer



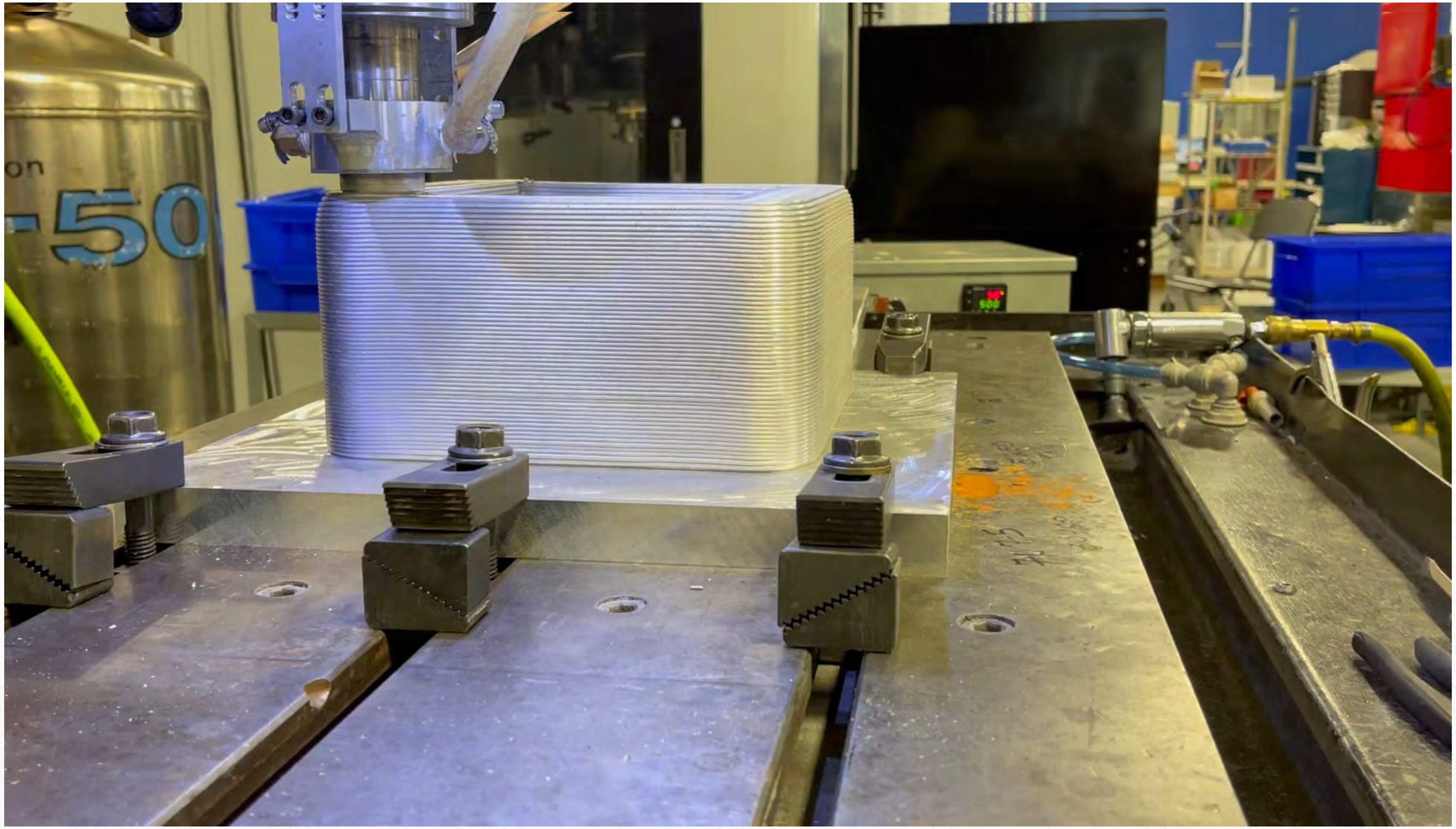




MELD MANUFACTURING

Additive Friction Stir Deposition (AFSD) equipment, processes and components.

AA 7075 Printing – One Reason I'm Still Interested in SCC



Thank you very much!

Australian Government
Department of Defence
Defence Science and Technology Group

DSTG Intergranular Corrosion of 7000 series aluminium alloys

Grant McAdam, Alison Wythe, Chris Loader

Presented at the Technical Interchange Meeting on Environmentally Assisted Cracking of 7XXX Aluminum, Dayton, Ohio 5-6 Nov. 2024

- DSTG Program
  - Outdoor exposure – uncoated
  - Outdoor exposure – coated
  - Thermal exposure
  - Use of Corrosion Prevention Compounds (CPCs)
  - In-service failures
  - Laboratory grown intergranular corrosion (IGC)
  - IGC and Fatigue

Outdoor Exposure - Uncoated

Research Summary

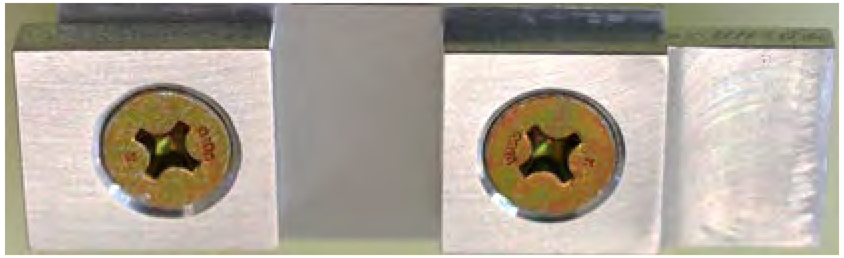
- Range of Environments
- Different storage locations
- Different Alloys
    - AA2024
    - AA2124
    - AA7050
    - AA7085

Risks/Issues

- Potential for corrosion not experienced on legacy alloys

DSTG Responsibilities

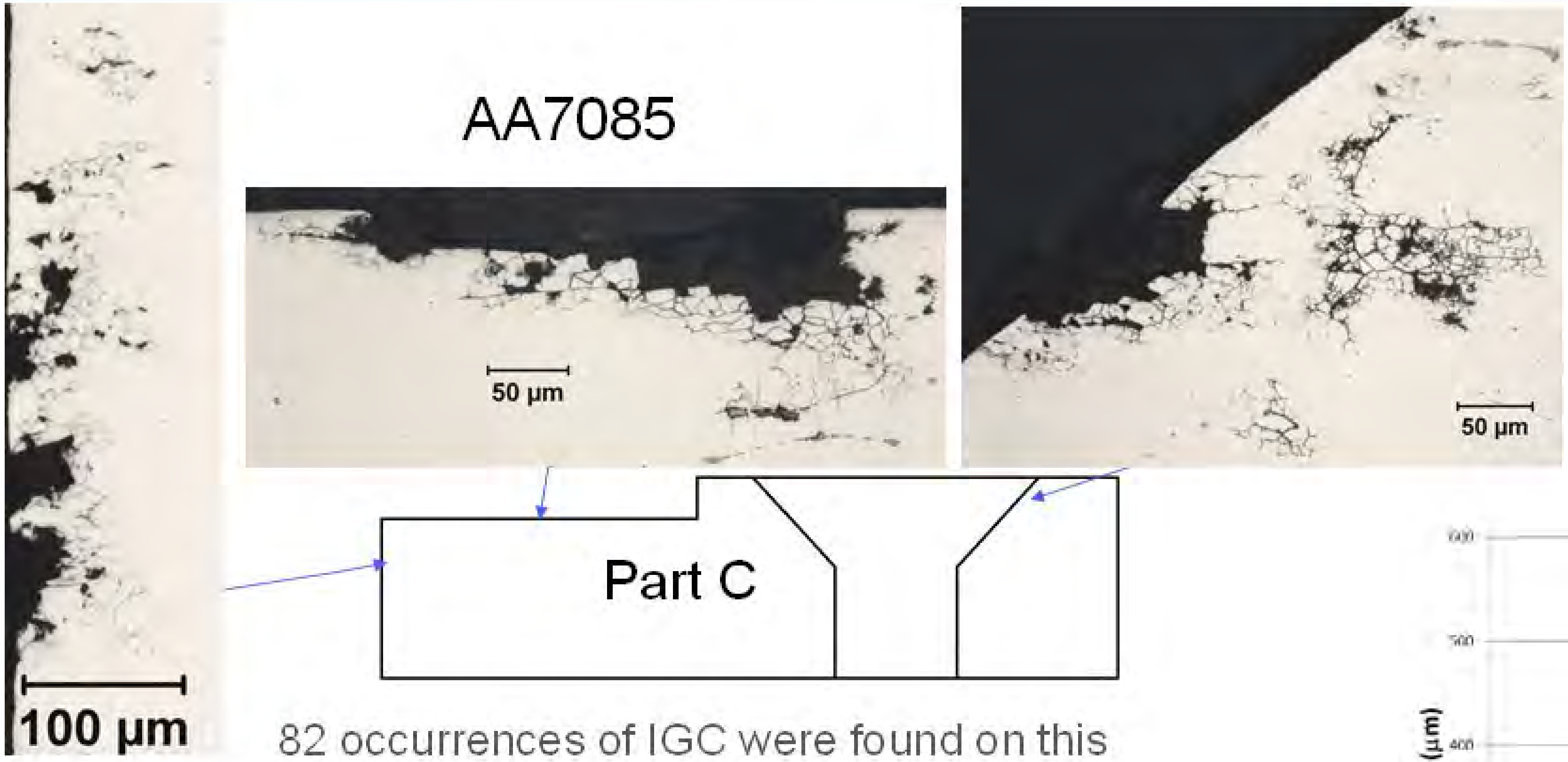
- Conduct Exposure
- Assess extent of Corrosion



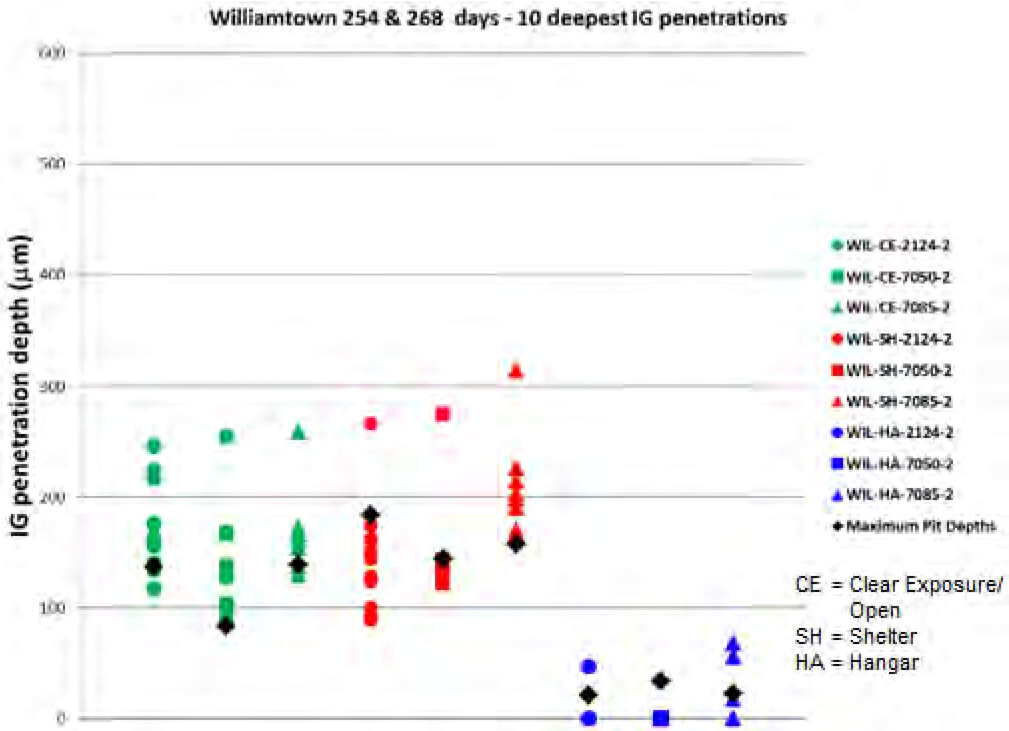
Outcomes

- IGC greater than expected
- Shelter more severe than open
    - Wetter for longer and no removal of salt build-up by rain washing

Outdoor Exposure – Uncoated - continued



82 occurrences of IGC were found on this section – Shelter at Williamtown after 268 days



OFFICIAL

Outdoor Exposure – Coated & Scribed

Research Summary

- Assessing the ability of coatings systems to prevent corrosion

Risks/Issues

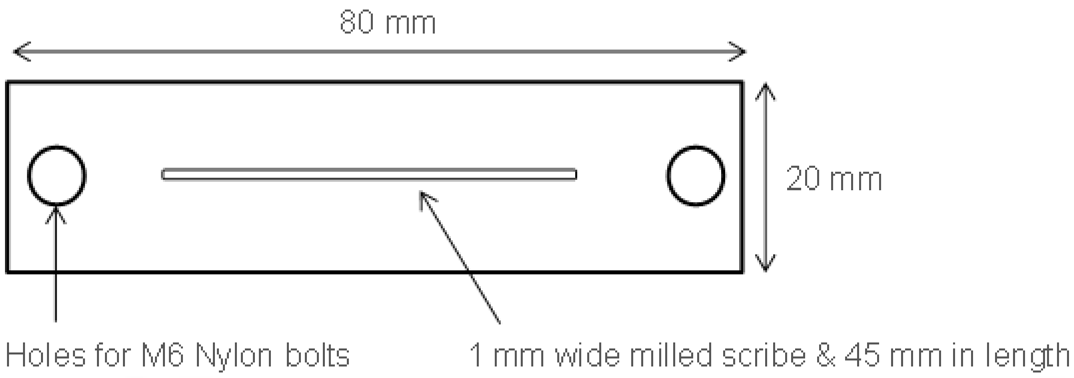
- Performance of chromate-free primer does not prevent corrosion

DSTG Responsibilities

- Outdoor performance testing of coated AA7085 against chromate containing controls

Outcomes

- IGC continued to progress with time



IGC of AA7085 + Anodize + Non-Chromate Primer + Topcoat

	3 months		6 months		12 months	
	Max. IG Length (µm)	Max. IG Depth (µm)	Max. IG Length (µm)	Max. IG Depth (µm)	Max. IG Length (µm)	Max. IG Depth (µm)
Open	229	120	416	96	420	113
Shelter	559	98	1271	172	1651	197
Hangar	31	20	-	-	71	48

Research Summary

- Range of durations and temperatures assessed for impact on corrosion performance

Risks/Issues

- Does repeated thermal cycling lead to increases in corrosion

DSTG Responsibilities

Alloys: AA7050, AA7085

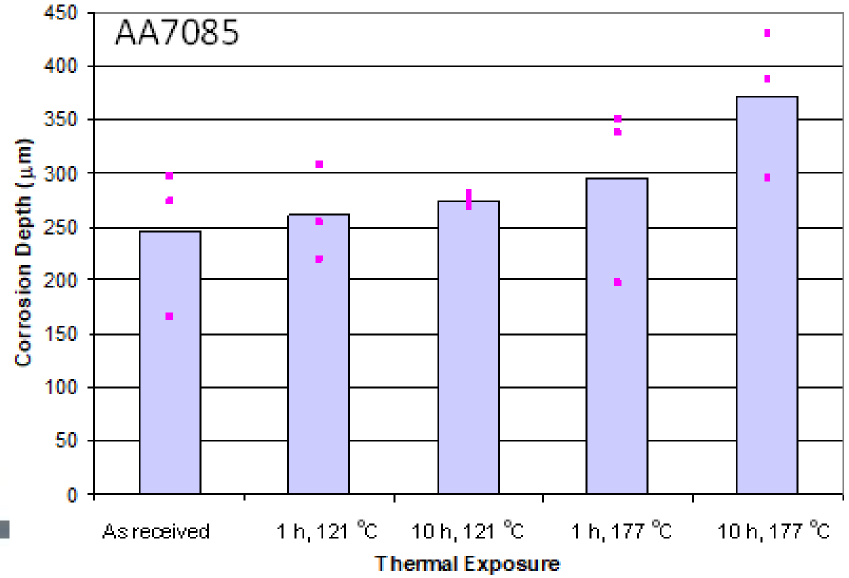
Thermal exposure: 1 & 10 h at 121 °C
1 & 10 h at 177 °C

Corrosion Tests: Electrochemical
Susceptibility to exfoliation corrosion
Droplet testing

AA7085 after 10 h at 177 °C

Outcomes

- Thermal cycling does lead to increases in corrosion damage



Research Summary

- Aluminium Alloy 7085
  - Faster, cheaper forging
  - Susceptible to IGC
  - DSTG convinced Defence of need for corrosion mitigation strategy
  - Long term outdoor exposure of AA7085 with coating stack-up to evaluate performance

Risks/Issues

- NDI techniques do not reliably detect IGC
- Repairs of corrosion do not effectively remove IGC damage and it is the initiation point for future corrosion

DSTG Responsibilities

- Outdoor exposure testing of AA7085
- Conduct trial to assess the effectiveness of NDI techniques and corrosion repairs to remove IGC

Outcomes

- Improved understanding of the impact of IGC on maintenance activities
- Advice on risk of continued operations in the presence of IGC
- Advice on repair procedure ability to manage corrosion in bulkhead material
- Assessment of unserviceable component due to corrosion damage (AA 7050)

Research Summary

- Fastener hole corrosion treated with CPC to arrest corrosion
- Are CPCs affective at arresting pitting and IGC

Risks/Issues

- CPCs are ineffective at arresting corrosion
- On-going corrosion related maintenance burden likely to increase

DSTG Responsibilities

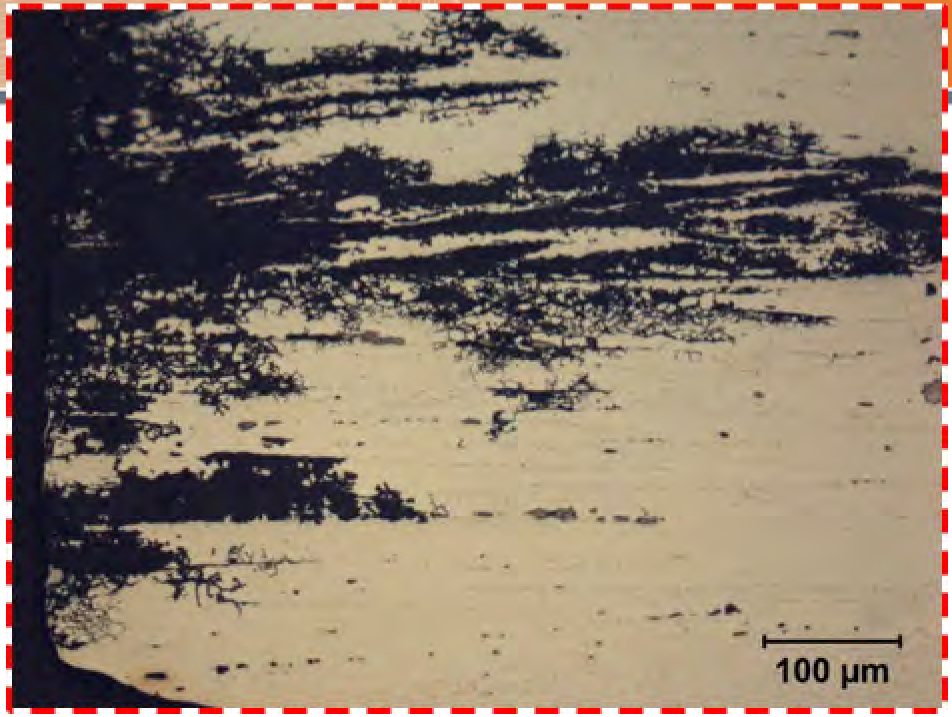
- Assessed CPC (Esgard) that was being used by the RAAF
- Extend program to a CPC recommended by the Original Equipment Manufacturer

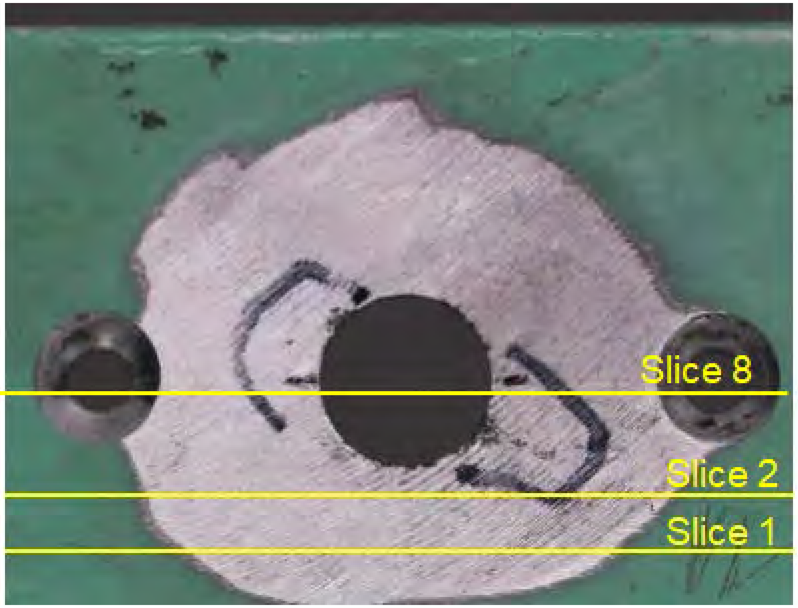
Outcomes

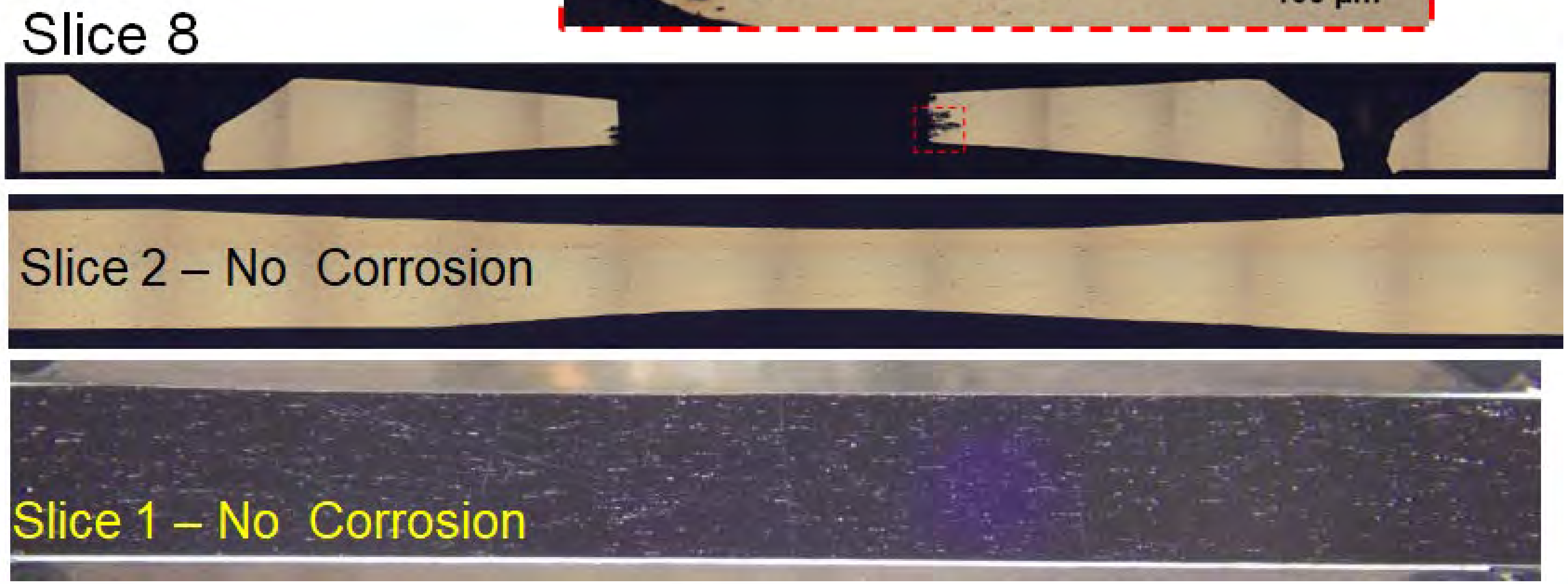
- Rapid assessment of CPCs for corrosion deferral
- Support introduction of CPCs as standard repairs within the program
- Use of CPCs will reduce the incidence and extent of fastener hole corrosion reducing the maintenance burden

In-service corrosion example - 1

- Significant attempts to remove surface corrosion from AA7050 had taken place before component was deemed unserviceable
- DSTG tasked to characterise remaining corrosion





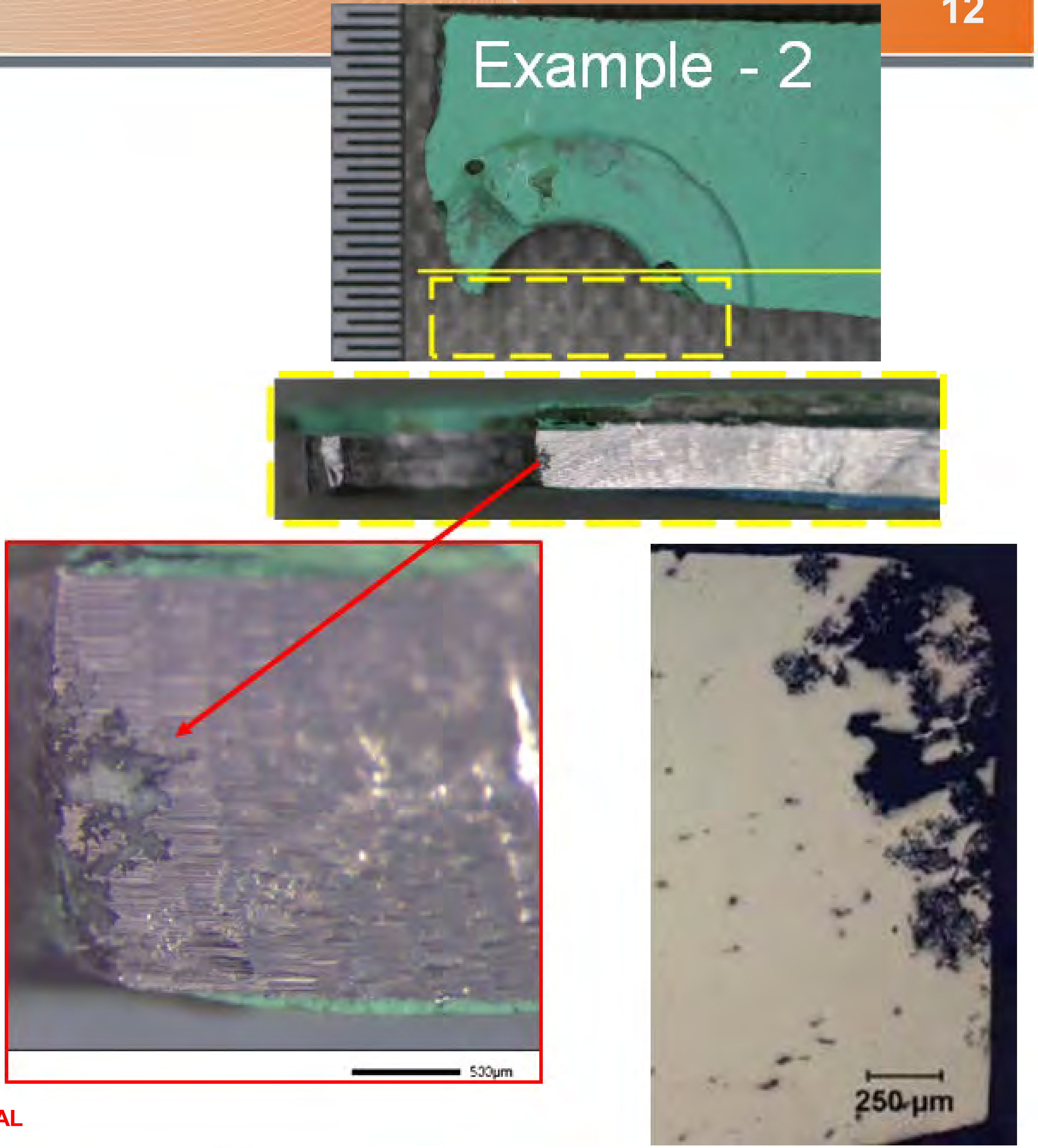


Findings Summary

- Significant corrosion penetrations from hole bore
- Maximum penetration approx. 1200 μm
- Corrosion occurring in satellite holes
- Corrosion detected underneath coatings and sealants
- Presence of fine IGC networks confirmed, which are difficult to detect without destructive analysis
- Corrosion identified in a hole, not flagged as having corrosion present

In-service corrosion example - 2

- Cut outs from failed component provided to DSTG for destructive analysis
- Corrosion **<u>had not</u>** been cleared during the course of the maintenance on the aircraft
- Corrosion was still being detected
  - Never got to a clearing point within permitted damage limits and was the reason the material had to be excised
  - Bathtub repairs implemented
- Material AA7050



Research Summary

- To grow IGC down fastener holes on AA7085 that
  a) Grows at a predictable rate
  b) Represents characteristic form of fleet corrosion
  c) Represents characteristic size of fleet corrosion

Risks/Issues

- Not possible to replicate microstructure in form and size
- IGC adversely impacts fatigue

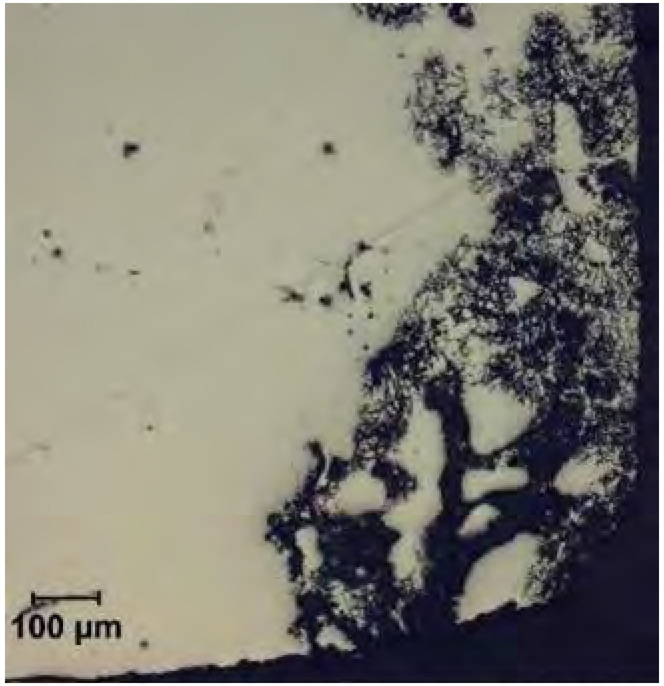
DSTG Responsibilities

- Grow IGC guided by in-service corrosion
- Adapt ASTM G110 or develop electrochemical methods to grow representative IGC

- Acknowledgement: Maria Salagaras, Nick Tugwell & Rainier Catubig

Outcomes

- Development of a test to representatively grow IGC



In-service corrosion on AA7050

IGC as found in-service

Extensive IGC or pitting

Lab-grown corrosion on AA7085 with ASTM G110 solution

IGC Summary

- ASTM G110 – Standard method for evaluating Intergranular corrosion resistance of 7000 series Aluminum alloys
- Immersion of AA7085 specimens in a solution containing NaCl and H_2O_2 as described in ASTM G110 for times ranging 6 - 96 h
- Results so far;
  - 300 µm fine IGC networks after 24 h
  - Maximum penetration of 500 µm, after 96 h (4x exposure), with significantly less IGC present
- Beyond 24 h exposure time, penetration from hole slows down significantly, and tendency to form bulk pits increases
- Future work: refine procedure to grow larger, finer networks, rather than bulk pits

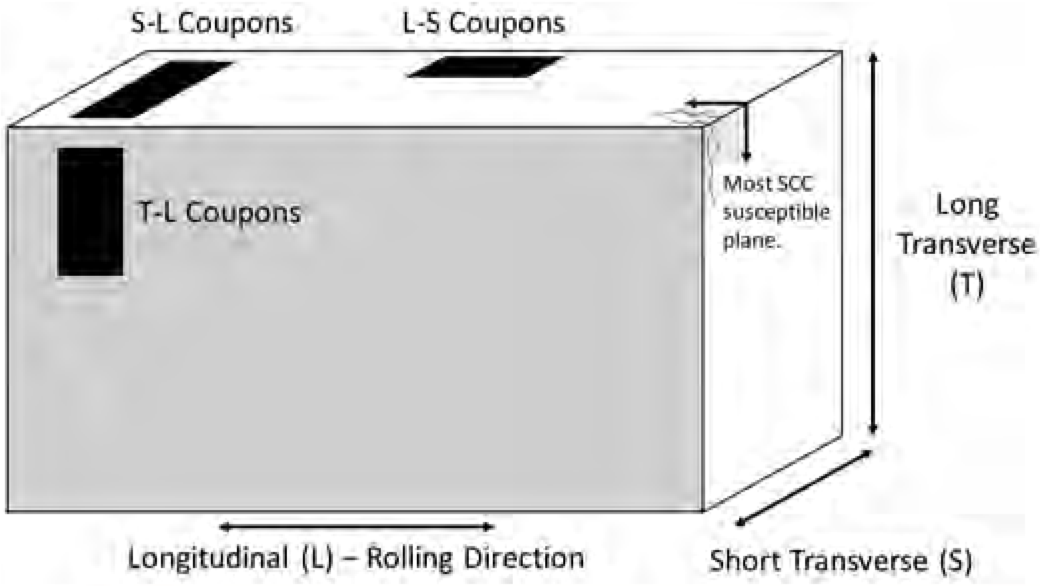
Fatigue Crack Growth (FCG) from IGC and Corrosion

- Aim: better understand the risk posed by fatigue cracks growing from corrosion pits/IGC
- Method:
  - Introduce corrosion/IGC at hole in AA7085 coupons, then fatigue test
  - Perform QF to document fatigue nucleation and growth
  - Compare non-corroded to corroded
  - Acknowledgement: Isaac Field & Ben Dixon

Coupons ≈ 160 mm × 80 × mm x 5 mm
3 orthogonal orientations from 6" thick AA7085 forging

Test Matrix

Orientation	Hole condition	Stress (MPa)	Coupons
L-S	As-machined	≈ 130	5
L-S	Corroded	≈ 130	5
T-L	As-machined	≈ 130	5
T-L	Corroded	≈ 130	5
S-L	As-machined	≈ 130	5
S-L	Corroded	≈ 130	5



Summary

- DSTG Program
  - Outdoor exposure – uncoated
  - Outdoor exposure – coated
  - Thermal exposure
  - Use of CPCs
  - In-service failures
  - Laboratory grown IGC
  - IGC and Fatigue

- The authors would like to acknowledge the rest of our team whose research has contributed to this presentation:
  - Maria Salagaras
  - Nick Tugwell
  - Rainier Catubig
  - Ben Dixon
  - Isaac Field

Questions?

[dstl] The Science Inside

UK MOD Response to EAC of 7000 series Al Alloys

Dr David Hallam, Air Work Package Technical Lead, Dstl Advanced Materials Programme

Prepared by: Joe Plummer, Dstl Senior Scientist

Ministry of Defence

BLUF Slide – UK MOD Response to EAC

[dstl] The Science Inside

- 1710 Naval Air Squadron and Dstl carried out rapid investigation of coupons from LII airframe forging (7085 T7452) based on EASA SIB 2014-04
  - Testing was primarily to confirm susceptibility to cracking
  - Results showed positive result for EAC in 7085 (T74)
- University of Manchester tasked through DMEx to deliver two year task on EAC for defence aviation-specific alloys and environments
  - Aims to understand effect of environmental factors (inc chloride exposure) to crack life cycle of 7085 T7452
  - Project will develop test procedures to allow real-time monitoring through life of crack (initiation, short to long cracks)
  - Will also explore generation of statistical data sets to inform digital twin/active learning for crack initiation and growth – to support inspection regimes and potential crack management approaches
- UK MOD interested in engaging on international research collaboration
  - DMEx designed to facilitate IRC, including exchange of staff and collaborative projects

Current UK MOD Involvement in EAC Issues

[dstl] The Science Inside

- Lightning II Delivery Team – DE&S
  - Providing representative material (forgings) for ongoing testing 1710 NAS & University of Manchester.
  - Convened meeting with JPO on publication of EASA SIB
  - Participation in F-35 Corrosion Prevention Advisory Board and Aircraft Structural Integrity Program meetings
- 1710 Naval Air Squadron
  - Carried out initial testing against EASA SIB
  - Providing support to in-service platform failures and issues
  - Participating in JSF Corrosion Prevention Advisory Board
- Dstl
  - Formulating and delivering S&T research related to EAC
  - Supported initial testing against EASA SIB
  - Engaging in international materials S&T collaboration

UK MOD Replication of EASA SIB 2014-04

- Once made aware of the SIB publication, 1710 Naval Air Squadron and Dstl carried out a rapid investigation of coupons from LII airframe forging (7085 T7452)
  - Testing was primarily to confirm susceptibility to cracking (with quick time to failure), not to develop understanding of initiation or growth of cracking
- C-rings (as specified in ASTM G38) produced to load in the ST grain direction
  - 6x c-rings produced per material
- Samples loaded and placed in conditioning chamber, with aim to run for 100 days
- Samples examined every 7 days to identify crack development

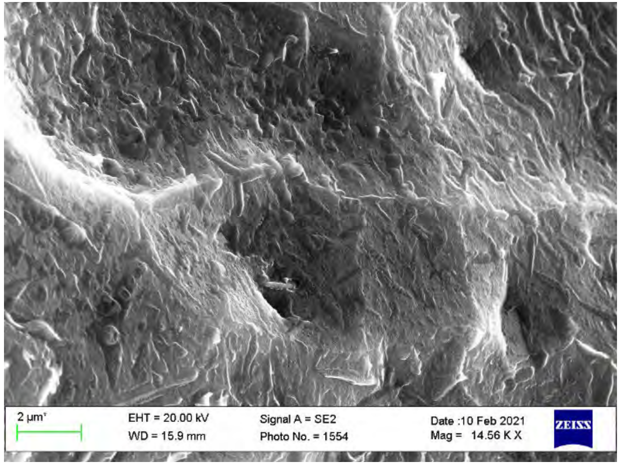
Materials	7085 T7452 7085 T7451 7050 T7451
Temperature	70^{o}C+/-1^{o}C
Humidity	85%+/-5%
Stress	85% YS

Test conditions for UK MOD replication of EASA SIB 2014-04

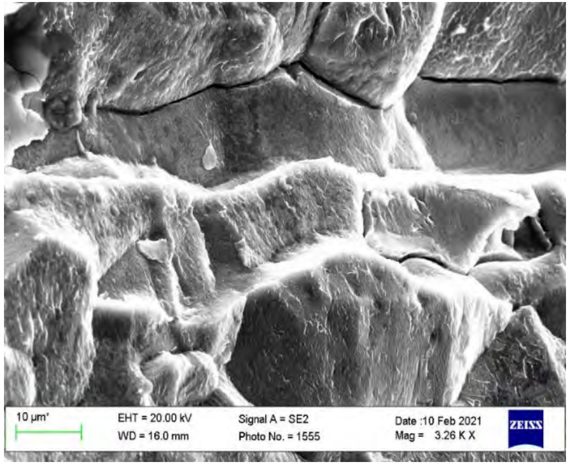
UK MOD Replication of EASA SIB 2014-04 - Results

[dstl] The Science Inside

- After 10 weeks, 4x7085 forgings and 3x7085 plates developed cracking
  - Experiment halted at 12 weeks due to cabinet failure
- Micrographs revealed features aligned with brittle intergranular fracture as seen in the SIB



7085 T7452 forging fracture surface, including GB precipitates standing proud



7085 T7452 forging fracture surface, including gaping GBs

UK MOD Response to EAC Testing Results

[dstl] The Science Inside

- MOD planned to repeat c-ring tests and run for full 100 days, however possibility of EAC in F-35 structure and output from University of Manchester viewed as sufficient evidence to proceed with research task
  – Initial Manchester work focused on tempers and conditions for civil aviation applications. Direct tasking required to address UK MOD key questions
- Initial research on susceptibility of alloys of interest to MOD planned between Dstl, 1710 and University of Manchester
  – Issues with recruitment prevented work from commencing
- New research task with Manchester now planned through the Dstl Defence Materials Centre of Excellence (DMEx)
  – Understand susceptibility of in-service alloys for defence aviation
  – Rebuild metallurgy expertise necessary to support development and selection of future alloys

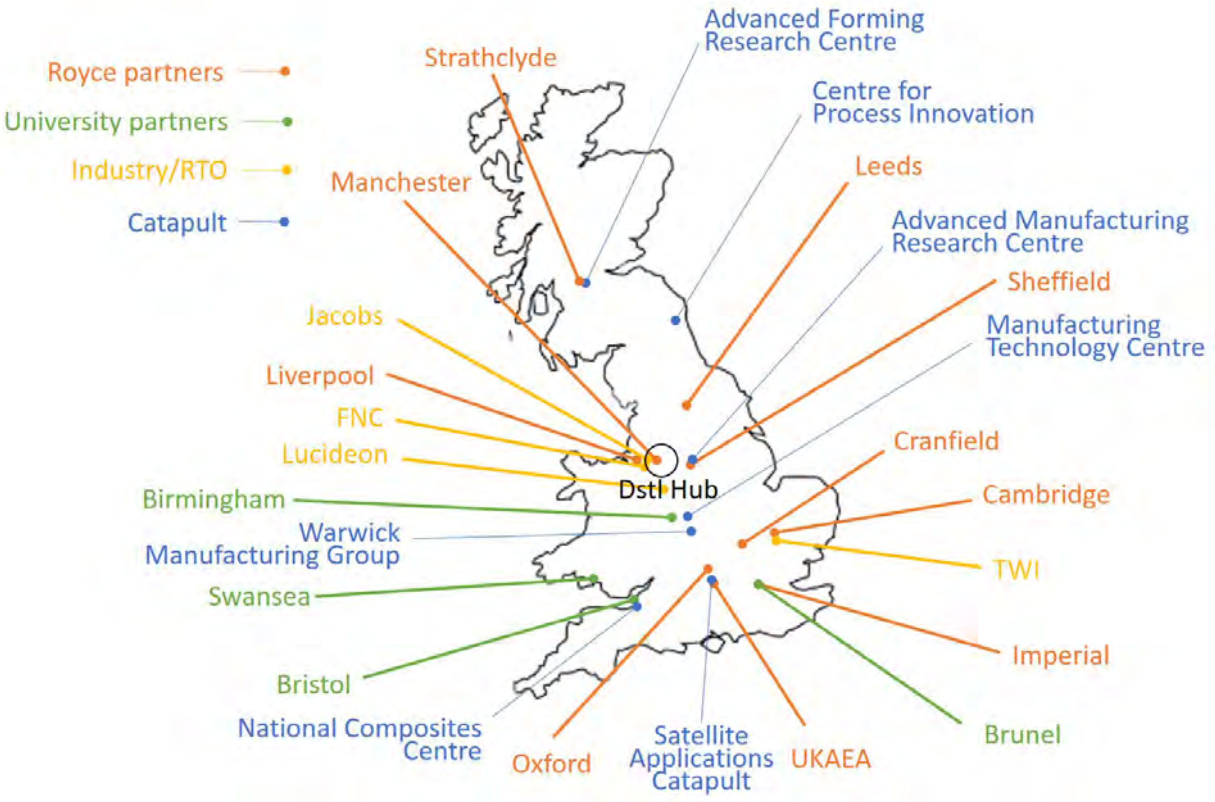


Image courtesy University of Manchester

Dstl contract with the University of Manchester

UoM the legal entity that leads the Henry Royce Institute (HRI) - UK's national institute for advanced materials research and innovation

£42.5M over 5 years from 01/12/2023 (includes S&T, Man & Gov)

HRI a Hub and Spoke model – UoM the hub

Dstl's Centre is HRI plus:

- Other university centres of expertise in important fields, e.g. composites, high temperature testing…
- High Value Manufacturing Catapult
- Satellite Applications Catapult
- Research and Technology Organisations
- Industry

A partnership

DMEx Task on EAC of Naval Aviation Al Alloys

[dstl] The Science Inside

- University of Manchester tasked through DMEx to deliver two year project on EAC for defence platforms
  - Aims to understand effect of environmental factors (including chloride exposure) to crack life cycle of 7085 T7452
  - Project will develop test procedures to allow real-time monitoring through life of crack (initiation, short to long cracks)
  - Will also explore generation of statistical data sets to inform digital twin/active learning for crack initiation and growth – to support inspection regimes and potential crack management approaches
- UK MOD (Dstl, 1710 NAS and LII DT) to provide ongoing support to task and aid translation to in-service support
- Future work may support wider Air Materials efforts:
  - Potential to further develop models as part of Air Digital Twin thread
  - Developed tests and models could be utilised to de-risk development of future materials
    - Within scope of DMEx to support MOD “intelligent customer” status, but not lead development of new alloys

MOD position on international collaboration on EAC

[dstl] The Science Inside

- UK MOD interested in engaging on international research collaboration
  - DMEx designed to facilitate IRC, including exchange of staff and collaborative projects
- Multiple routes to information sharing and indirect collaboration
  - Dstl utilise range of programmes and MOUs inc. TTCP, NATO AVT and AUKUS
  - 1710 active in JSF CPAB
- Direct collaboration (including sharing materials and data) in a timely manner will require planning and selection of suitable IRC programme
  - Recommend early engagement with relevant IRC leads to identify appropriate channel

[dstl] The Science Inside

Discover more

Dedicated to innovation in aerospace

NLR perspective

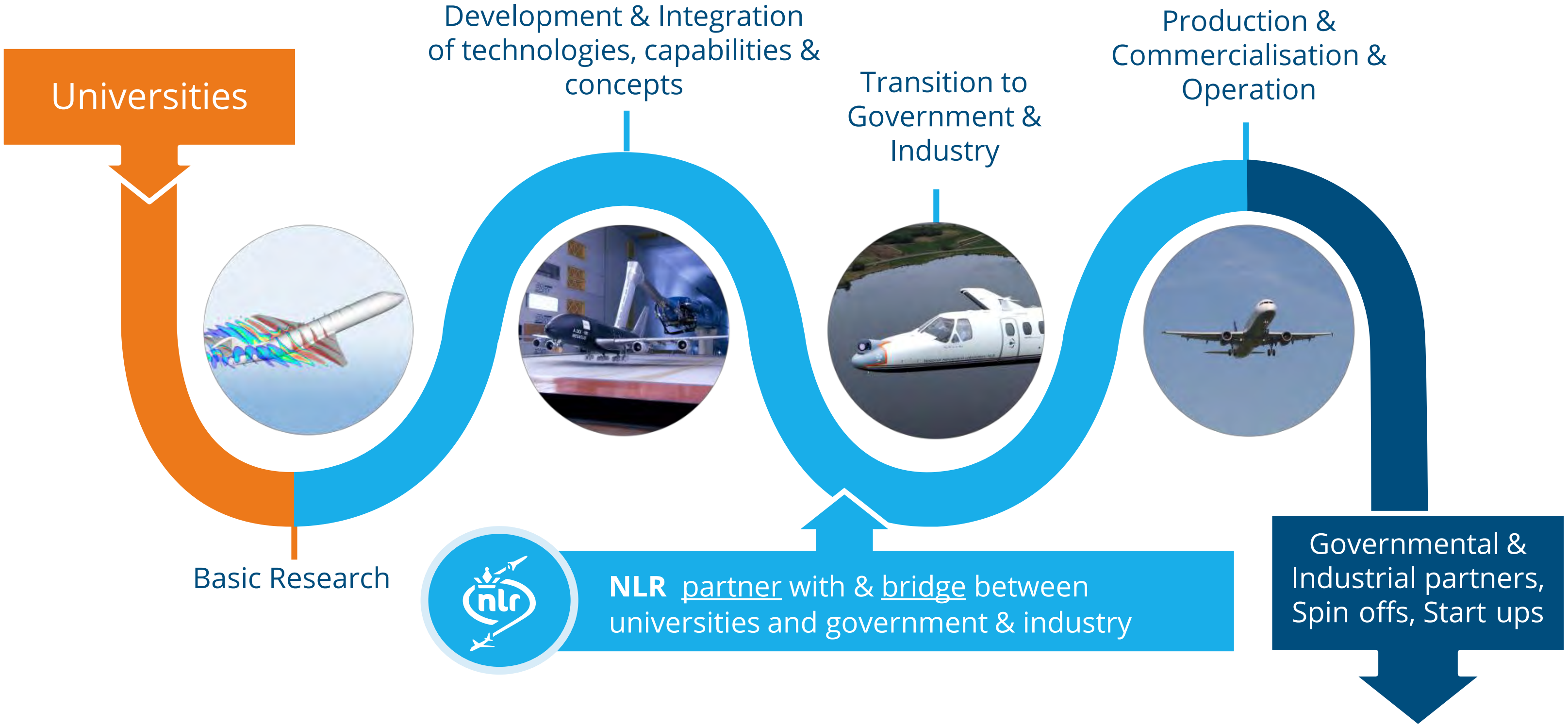
EAC in aluminium alloy 7085-T7452

Borit Zwerink

5 November 2024

Dayton, Ohio

The role of NLR



Multidisciplinary fields of knowledge

Aerospace systems

Aerospace operations

Aerospace vehicles

Photo credits: ESA – P. Carril , 2012

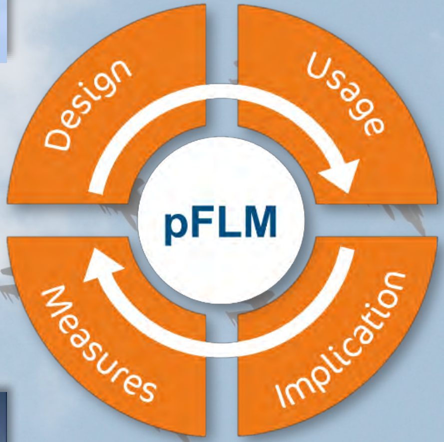
AVIL activities

Aerospace Vehicles Integrity & Life Cycle Support

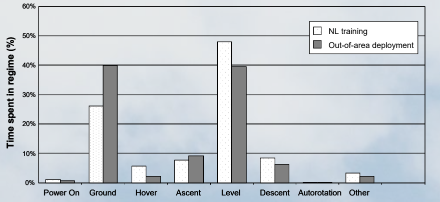
Some examples

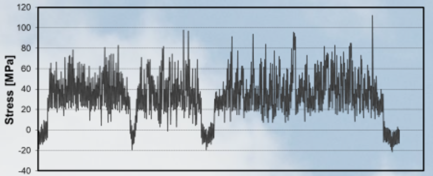




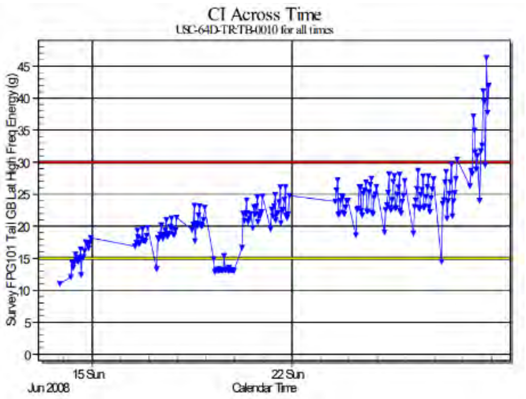


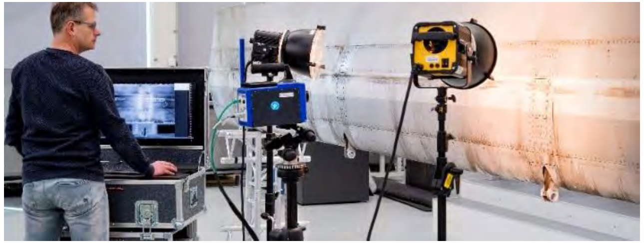


AVIL activities

Some examples



Predictive Mx

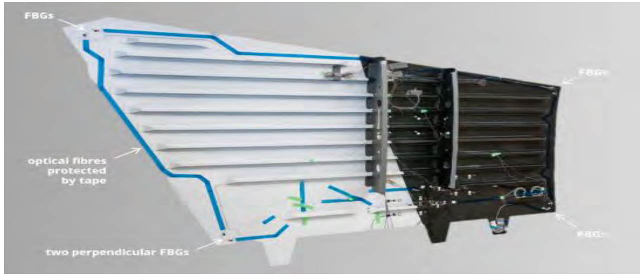


NDI/thermography

Mx tooling

ECTM

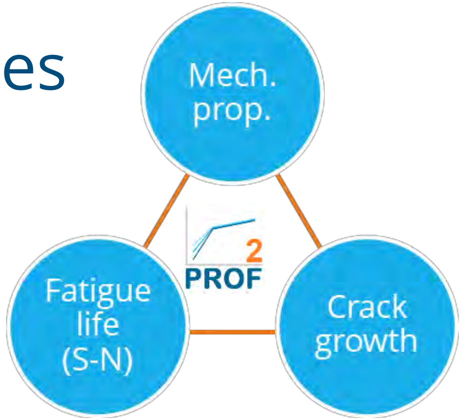
Data analytics

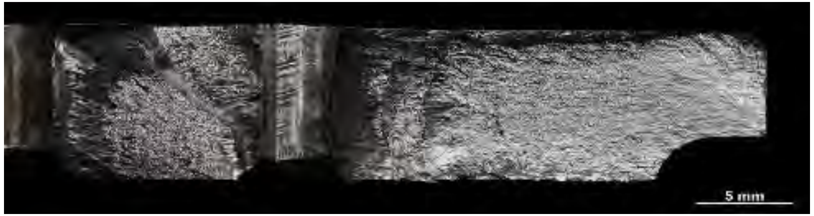


SHM/Impact Detection

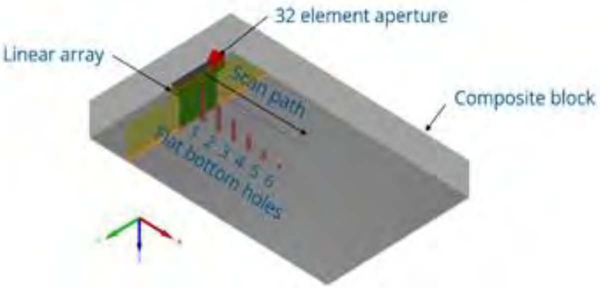
AVIL activities

Some examples

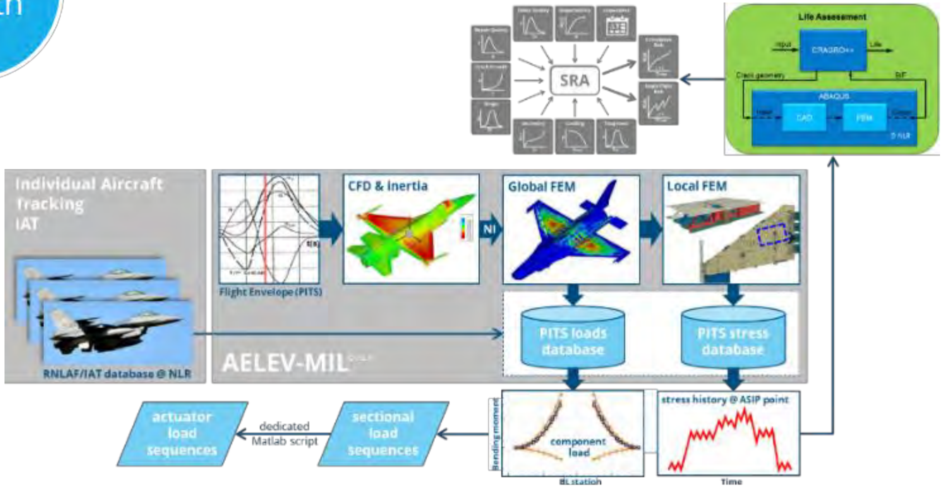




Prognostic failure models



NDI/MAPoD



Digital twinning

Environmentally Assisted Cracking

- EAC according to European Union Aviation Safety Agency (EASA)
  - Issued from 2018 Safety Information Bulletin (SIB)

EASA SIB No.: 2018-04R2

EASA
European Union Aviation Safety Agency

Safety Information Bulletin
Airworthiness

SIB No.: 2018-04R2

Issued: 04 March 2021

Subject: **Environmentally Assisted Cracking in certain Aluminium Alloys**

Revision:
This SIB revises EASA SIB 2018-04R1 dated 13 September 2018.

Ref. Publications:
None.

Applicability:
Type Certificate (TC) holders, Supplemental Type Certificate holders, equipment manufacturers, maintenance organisations, production organisations and aluminium alloy producers.

Description:
EASA received reports of brittle cracking of aluminium alloy components. Additional investigation of some new generation 7xxx series alloys has shown that these have a sensitivity to a phenomenon known as environmentally assisted cracking (EAC), when subject to certain conditions in the normal operating environment. The type of EAC encountered appears to be caused by hydrogen embrittlement along the grain boundaries, leading to crack initiation and subsequent propagation. These cracks typically start from holes or other areas of stress concentration and usually propagate in a plane perpendicular to the short transverse (ST) direction. This phenomenon has been linked to the chemical composition of the alloy, notably a high zinc/magnesium ratio, combined with low copper content. Brittle fractures have been reproduced under laboratory environment and cracking has proven to be driven by time exposure (ageing) and is not fatigue related, although further crack propagation under operative loads cannot be excluded.

- Brittle cracking
- Certain conditions in the normal operating environment
- Propagate in ST direction
- High zinc/magnesium ratio, combined with low copper content
- Not fatigue related
- No obvious corrosion reaction

Testing method proposed in SIB

Specimen:

- Specimen geometry: Round smooth bar → according to ASTM G49 and ASTM E8 Tension test
- Align longitudinal axis of specimen (loading direction) with the Material ST grain direction

Loading:

- Loading device: Test rig → In Style of ASTM G49
- Loading: Constant load / displacement → according to ASTM G49
- Load level: set at 85% Yield only → In the style ASTM G64

Environment:

- Level of Humidity: 85% ± 5% → Ref. 1)
- Temperature: 70°C ± 1°C → Ref. 1)

Test time:

- Test duration is recommended to be at least 100 days

- Similar to Airbus Test Standard

HEAC Testing according to Airbus Test Standard

a)

<u>Experimental Conditions</u>

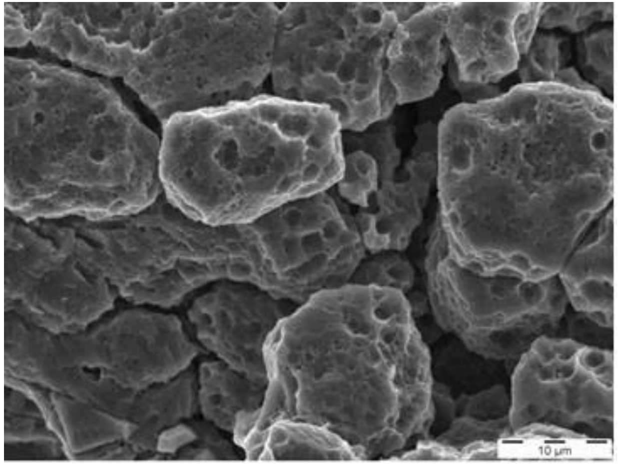
- **Specimen:** 60mm round bar
- **Load:** Constant 85 % Rp0.2 (70 °C)
- **Environment:** **air at different humidity levels**
- **Temperature:** 70°C

Testing at NLR

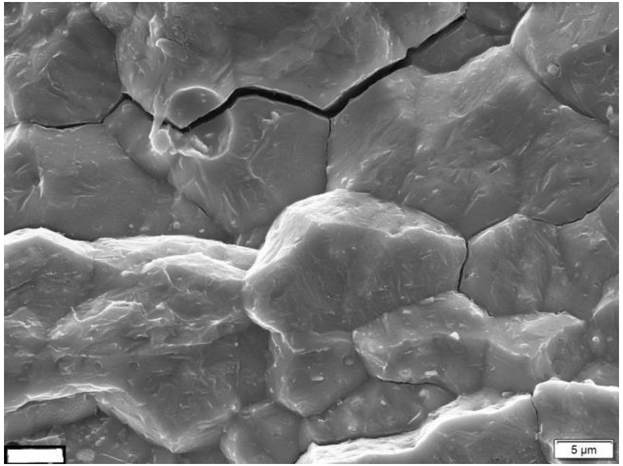
- Initial testing to get familiar with EAC in 7085-T7452
- Using ASCOR method
  - Automated Stress COrrosion Ring
- Constant loading at 85% of yield strength
- 85% humidity
- 70°C
- 12 specimen
- Currently 56 days in test
  - Since September 10

Definition of failure according to SIB

- Cracking along grain boundaries without corrosion attack or oxidation products
- If no cracking occured, check for presence of grain boundary cracking by optical examination
- SCC vs EAC fracture



Typical SCC fracture surface



Typical EAC fracture surface

Dedicated to innovation in aerospace

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[Airbus Amber]

AFRL-FAA Technical Interchange Meeting on Environmentally Assisted Cracking / Stress Corrosion Cracking of High-Strength 7000 Series Aluminium Alloys

Airbus Briefing

Export Control Not Listed. This Item is not listed against the EC regulations in the EU/FR

Zak Barrett, Senior Expert, Engineering Failure Analysis

Dayton, OH, 4 -5th Nov 2024

AIRBUS

Overview of the next 15 minutes.

- **Unexpected cracking of 7xxx Alloys from the perspective of an Airframer.**
  - How does Airbus define ‘unexpected cracking’
  - Where do we typically see the issue?
  - What are the typical fractographic characteristics?
  - How has Airbus investigated the humid air performance of 7xxx alloys?
  - **What are the key influencing factors from a service perspective?**
  - **How does Airbus ensure continued airworthiness?**

- **What are the 3-5 most critical questions that need to be answered?**
  - Short term, long term.
  - The need for a collaborative approach.

Unexpected cracking of 7xxx Alloys from the perspective of an Airframer.

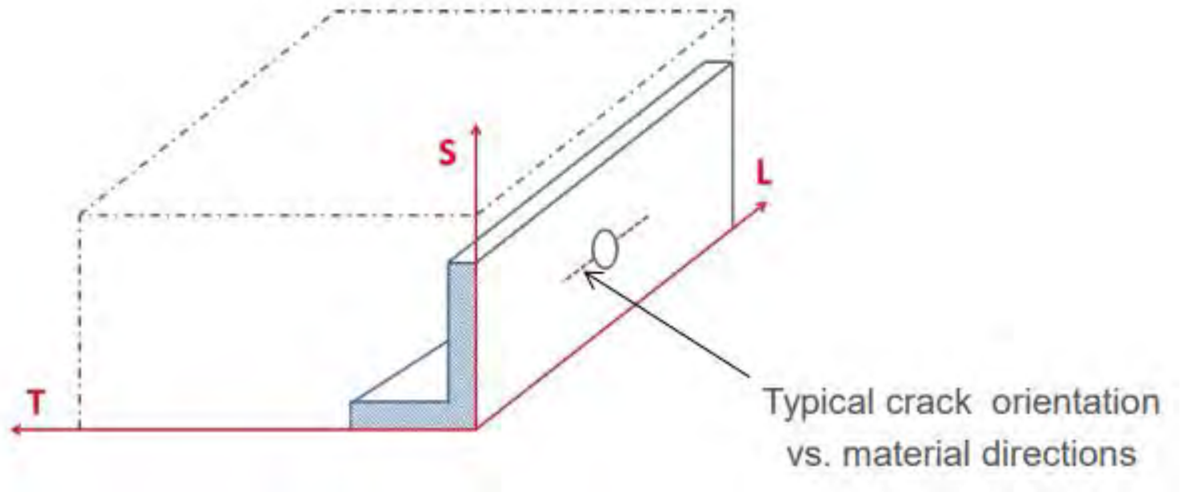
How does Airbus define 'Unexpected Cracking'?

Occurs in components that have:

- **Been manufactured from 3rd Generation 7xxx alloys that successfully passed the ASTM G47 qualification requirements.**
- **Designed using long established design principles have produced no cracking in otherwise technically identical components manufactured from 7010\7050 in a similar temper.**
- **Experienced cracking driven by exposure to the normal aircraft operating environment.**

Where does Airbus typically see the issue?

- Cracks typically initiate at the periphery of fastener holes and propagate in a plane perpendicular to the Short Transverse (ST) direction on the L-LT plane of the semi-finished product.



- Cracking can occur where standing stresses are present such as those induced by:
  - Build Stresses
  - Thermal effects.

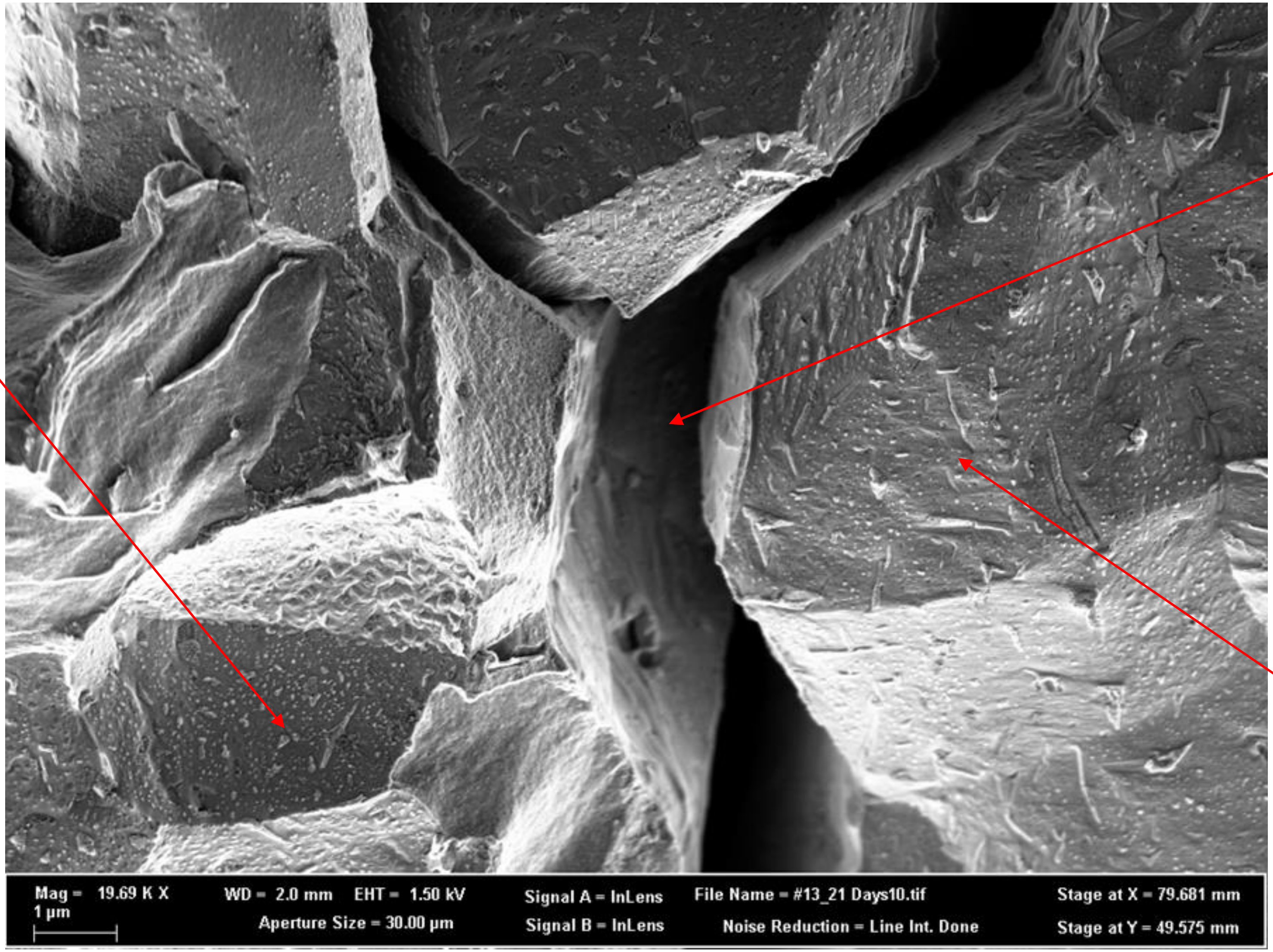
Monolithic design principles used successfully for decades.

No fracture of this type has been recorded in parts manufactured from 7010\7050-T7651 plate or forgings.

What are the typical fractographic characteristics?

Brittle mode of material separation

Gapping grain boundaries

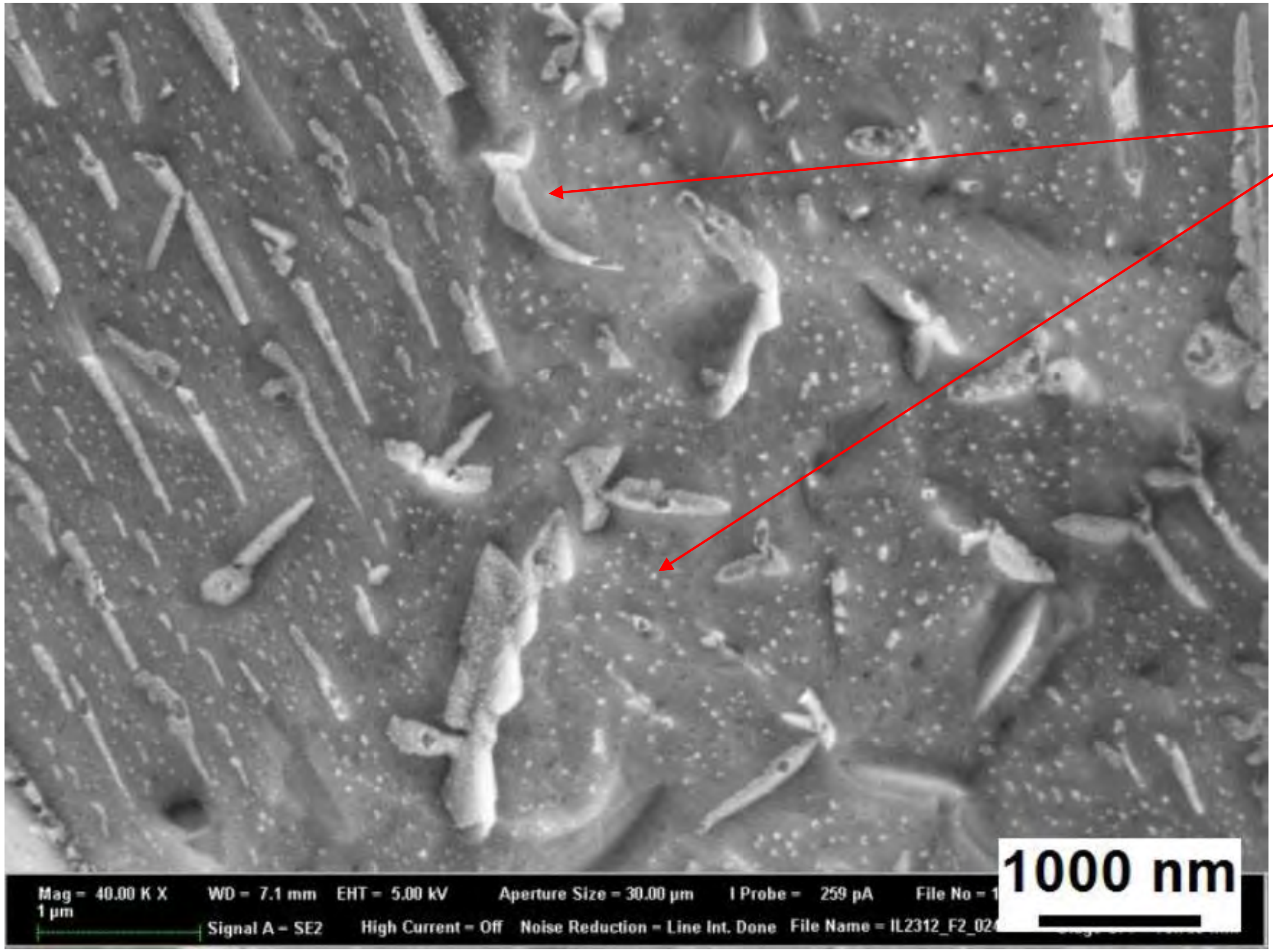


X20K

Little or no VISIBLE evidence of material dissolution on the fracture surface.

7085-T7651 Plate. Fracture morphology

The failure leaves a distinctive fractographic signature:



Intact grain boundary precipitates.

- **Specific imaging conditions are required to accurately identify HEAC as failure cause**:
  - SEM parameters optimised to resolve surface detail. E.g. Low Kv
  - >6000x magnification.

X40K

AIRBUS

How has Airbus investigated the humid air performance of 7xxx alloys?

Internal Test Work

Principle Aims: To understand the effect of:

- Stress
- Temperature
- Product form
- Alloy chemistry & temper

on susceptibility to cracking.

Publication Philosophy: Public Domain where possible with UoM

Academic Collaboration with University of Manchester

MANCHESTER 1824 The University of Manchester

Principle Aims: Detailed understanding of driving factors.

- Based on a comparative approach, 2nd vs.3rd generation alloys.

Prof. Joe Robson will present findings this afternoon.

Publication Philosophy: Public Domain

Internal Test Work: Approach

To accelerate the phenomena by stressing material samples at elevated temperature in a humid non-condensing environment. 70°C, 85%RH selected.

Time to Failure

Crack Growth Rate

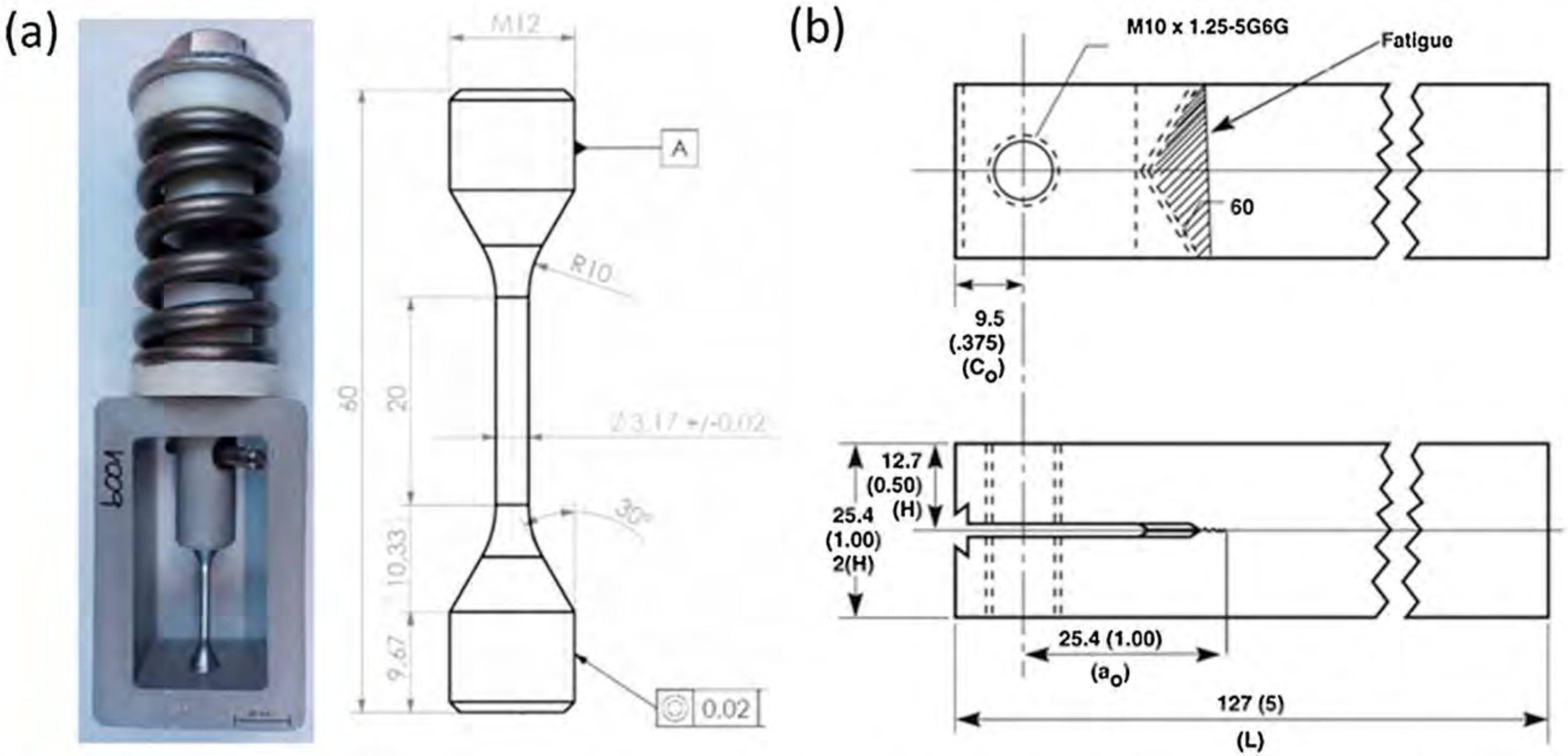
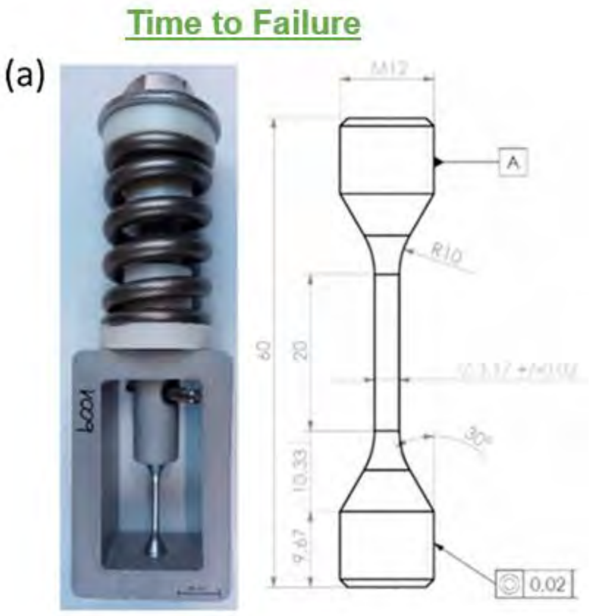
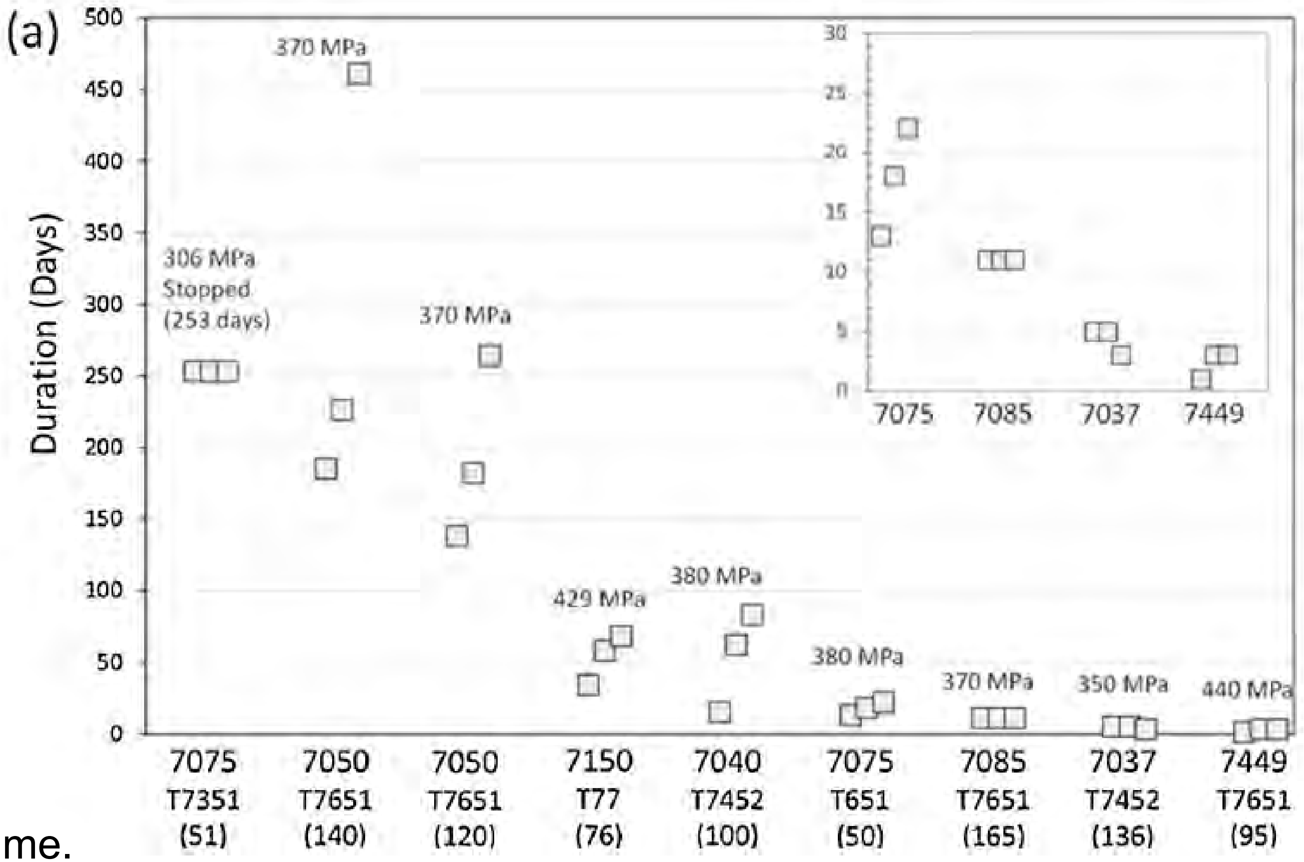


Fig. 2. The sample geometries employed in the accelerated test programme; (a) static load tensile (SLT) tests and (b) ASTM-G168 DCB crack growth samples.

AIRBUS

Accelerated test results - ranking materials by time to failure.





Test Conditions:
70ºC 85%RH 85%TYS(0.2
Note: Measured life is dominated by initiation time.

Lifetime of 3rd gen alloys is ~4% of 7010/7050-T7651
In-Practice: Crack initiation is more likely.

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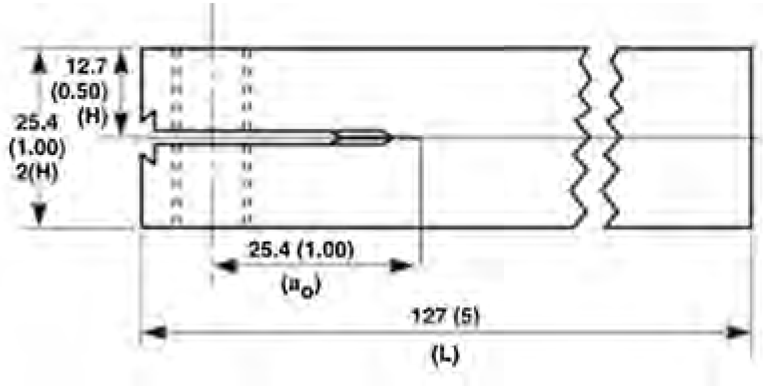
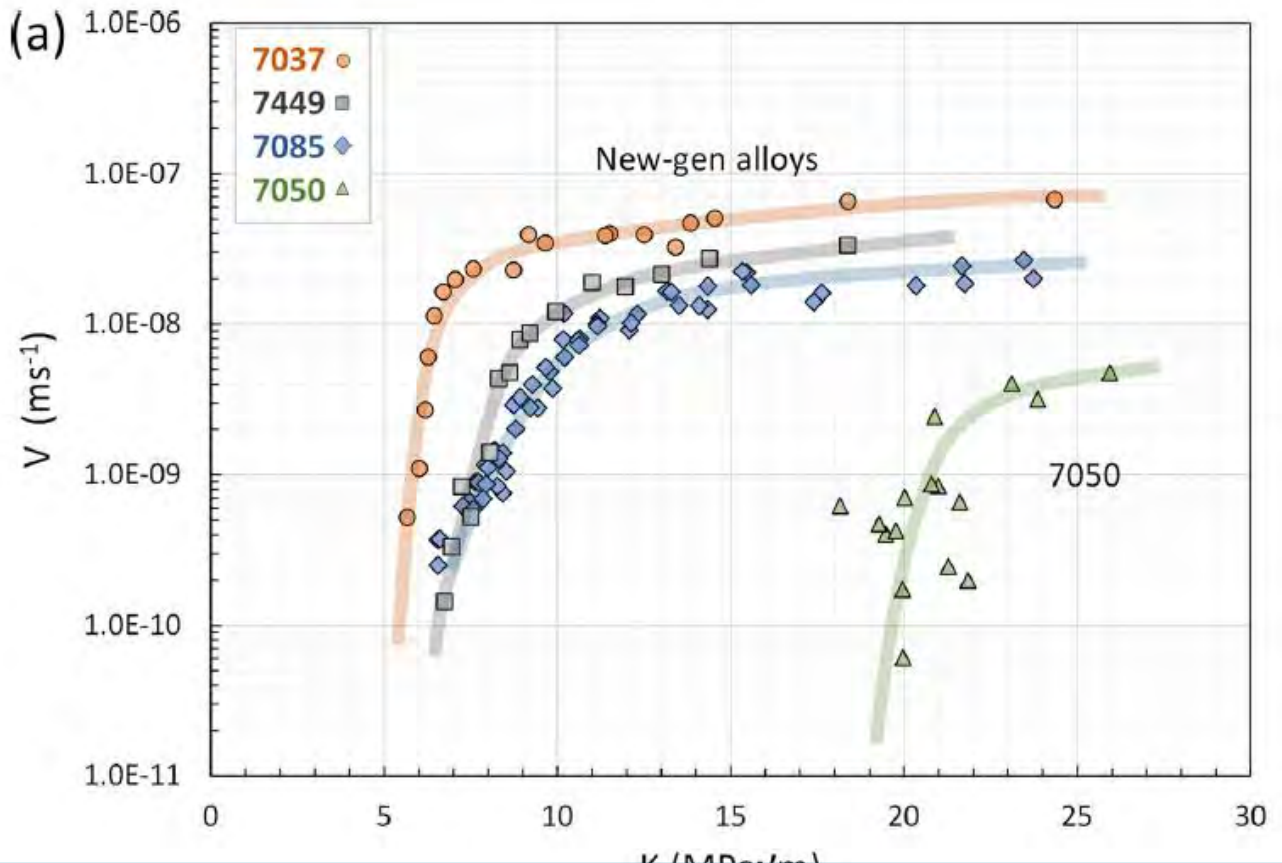
Accelerated test results - ranking materials by crack growth rate

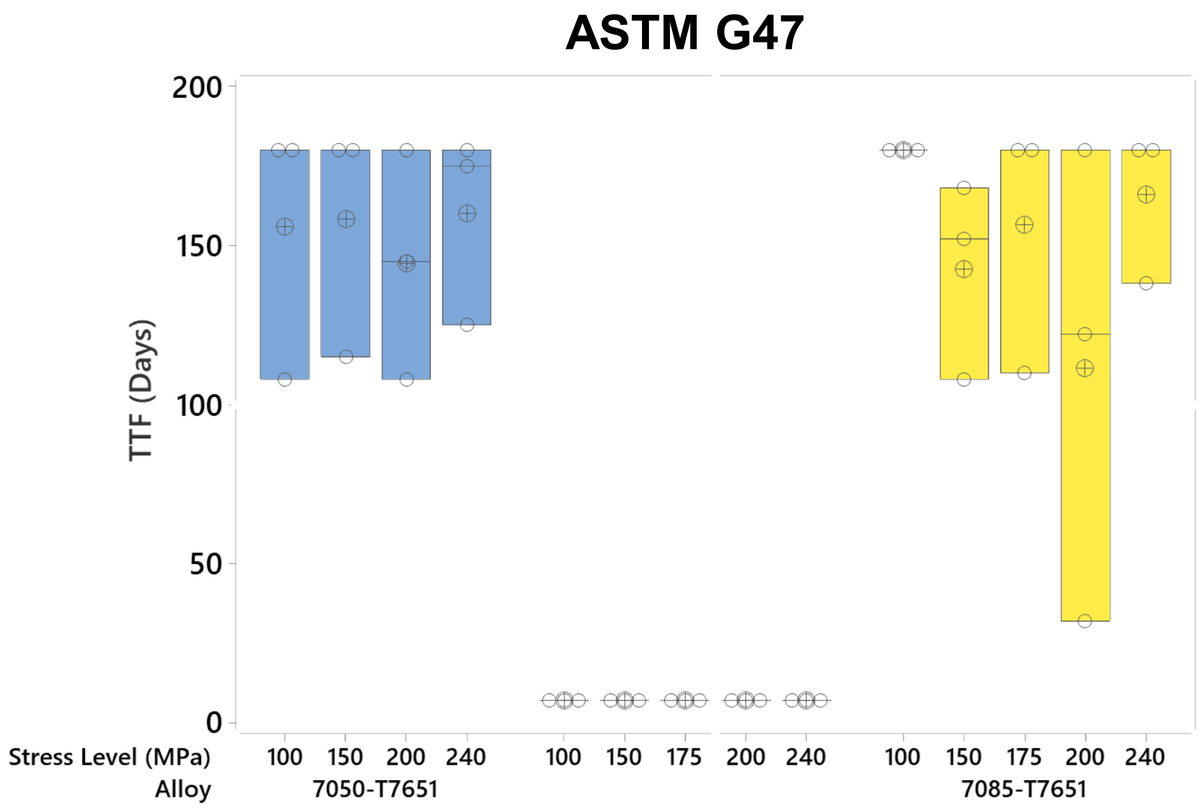


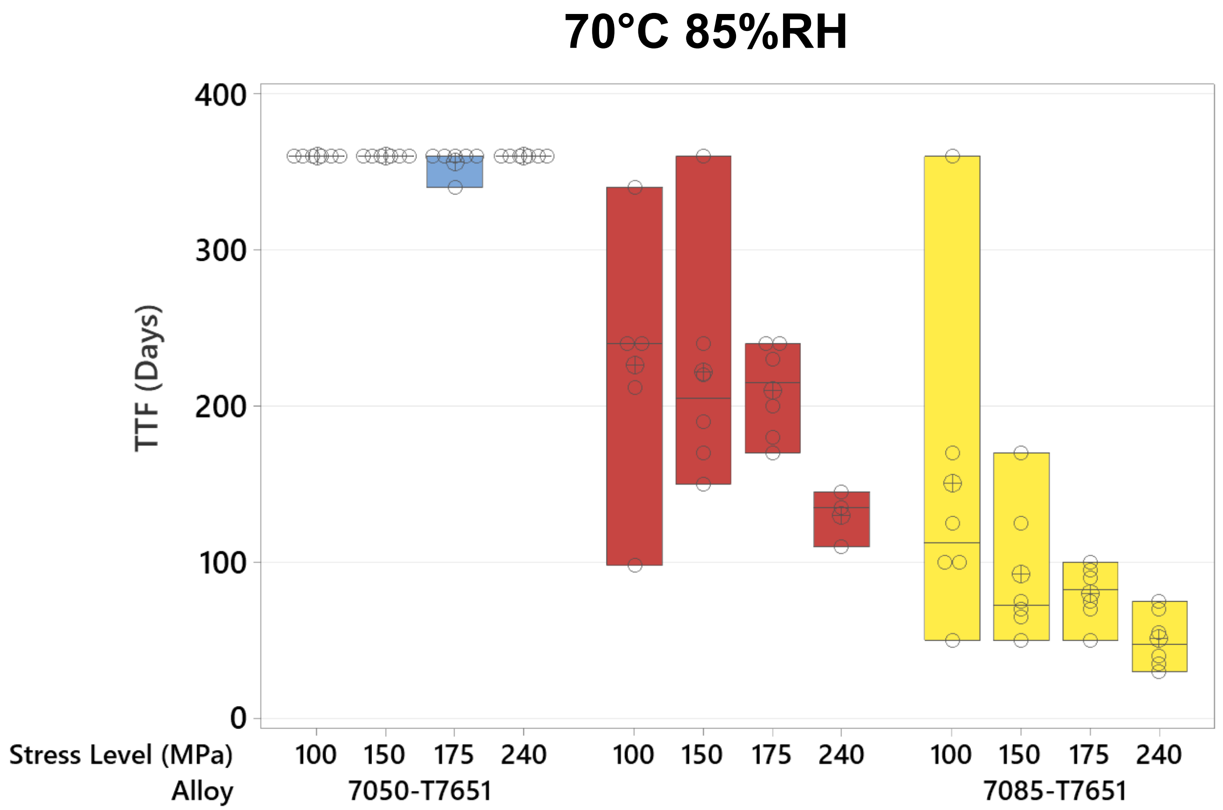


Test Conditions:
70ºC 85%RH 85%
Note: Falling K.
All alloys in the T7651 Temper
except 7037- T7452

V_{II} 3rd gen alloys ~6-20x 7050T-7651
K_{1HEAC} at least half 7050T-7651
In-Practice: Crack will grow faster and stop at a lower K_1.

The difference in ASTM vs. humid air response:





ASTM G47 does not reliably predict the performance of 7xxx alloys in the full range of environments that they may be exposed to.

Other learning points from humid air test work: 7050-T7651 vs 3rd Generation alloys.

- **The effect of relative humidity**
  – Above ~30%RH no change in time to failure observed.

- **The effect of temperature**
  – As temperature increases time to failure falls. The relationship is Arrhenius.

- **Other effects**
  - The material chemistry. Generally, a higher Zn:Mg ratio reduces humid air performance.
  - The temper. More overaging is better. A T74 is better than a T76.
  - The grain structure. The more elongated the grain structure, the worse the performance.
  - The plate thickness. Thicker plate is generally better than thinner plate.

In summary:

- 3rd generation alloys are much more sensitive to cracking in humid air.
- Increasing stress and temperature increases initiation and crack growth rate
- ASTM G47 does not identify this sensitivity.

Key learning points from service experience.

Service experience compliments laboratory findings.
Increasing stress, temperature and time at temperature all increase crack initiation and growth rates

AIRBUS

With this understanding, how do we manage airworthiness?

- Using the understanding from laboratory alloy performance ranking tests, we have a measure of the relative risk of cracking.
    - Using the rankings, we have taken the decision to remove 3rd generation alloys from the aircraft where sustained ST stresses are present, and replace with 7010\7050.
    - Where not possible, or not required, we have undergone a component by component assessment of cracking risk.

We ensure continued airworthiness by inspection and repair programs, reviewed and agreed with the authorities.

Most critical needs from an airframers perspective:

- **Short Term**
  - Industry wide agreement that 3rd generation alloys are sensitive to cracking in humid air.
  - Collaborative development of a new test method to complement G47. Reliable and quick prediction of humid air performance.

- **Long Term**
  - The development of physical models to enable prediction of cracking behaviour as a function of alloy chemistry, temper, stress level and operating environment.

Key Challenges: Complexity, which makes developing a reliable relationship between test performance and service performance difficult.

Open collaboration is essential to address the issue.
A multi-party, government-industry collaboration is needed.

Final Message:

- There is no doubt that the new generation of 7xxx alloys have an increased susceptibility to cracking in humid air relative to 7050.

- However, there are many uses of these materials where cracking does NOT occur and the full benefits of the alloy are realised.

- Therefore, use of a new generation alloy does not automatically mean you will experience HEAC cracking.

- An assessment of risk based on the factors discussed, coupled with inspection can be a practical management strategy.

Thank you

AFRL FAA TIM Dayton Ohio Not in Export Control List

ENVIRONMENTALLY ASSISTED CRACKING OF HIGH-STRENGTH 7000 SERIES ALUMINUM ALLOYS

AFRL FAA Technical Interchange Meeting (TIM) on Environmentally Assisted Cracking (EAC) / Stress Corrosion Cracking (SCC) of High Strength 7000 Series Aluminum Alloys

Nov 5th 6th, 2024

Mauricio C. Cunha Principal M&P Engineer Metallic Materials

SCOPE

- EAC / HEAC UNDERSTANDING
- EMBRAER EXPERIENCE WITH HEAC
- FINAL COMMENTS

EAC / HEAC UNDERSTANDING

- Environmentally Assisted Cracking (EAC): it refers to all cracking in metals that is aided by a chemical environment

- Stress corrosion cracking (SCC) and hydrogen embrittlement (HE) are types of EAC:

  – SCC (stress corrosion cracking): crack propagation driven by an anodic corrosion reaction at the crack tip
  – HE (hydrogen embrittlement): loss of a metal’s bond strength due to the presence of atomic hydrogen at grain boundaries and interstitial sites in the crystal lattice

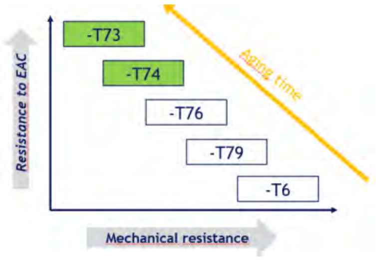
- Recent review and research papers use the term HEAC (hydrogen environmentally assisted cracking) for newer 7000 alloys prone to cracking in humid air

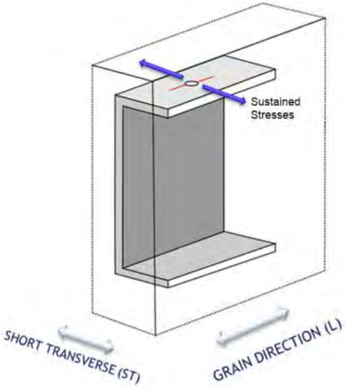
- Ref.:

  – Anderson, T. L. Fracture Mechanics: Fundamentals and Applications. 3 ed (2005) or 4 ed (2017)
  – De Francisco U. et al., Hydrogen environmentally assisted cracking during static loading of AA7075 and AA7449
  – Holroyd N. at al., Environment-Induced Cracking of High-Strength Al-Zn-Mg-Cu Aluminum Alloys - Past, Present and Future
  – Schwarzenböck E. et al., Environmental cracking performance of new generation thick plate 7000-T7x series alloys in humid air

HEAC UNDERSTANDING

- HEAC key influencing factors:
  - Susceptilble alloy (Al-Zn-Mg-Cu alloys, high zinc/magnesium ratio, combined with low copper content) and final temper
  - Sustained stress in a plane containing ST direction
  - Aging in a typical environment (time/temperature/humidity)





- Susceptible alloy and temper condition

  Ref.:
  - EASA SIB No.: 2018-04R2, Issued: 04 March 2021
  - Hereson, H. EASA presentation: EAC, STC Workshop, 2019

- Sustained stresses in the ST direction

- Time, temperature, humidity

EMBRAER EXPERIENCE WITH HEAC

- Embraer has been investigating this phenomenon since mid 2010´s*
  - Meetings with regulatory agencies
  - Embraer contacted aluminum suppliers / Test campaigns were set up
  - Laboratory testings performed under high humidity and high temperature
    - Tensile-bar (ASTM G49 style specimens)
    - Double Cantilever Beam (ASTM G168 style specimens)
    - Custom Interference Fit
    - Bending testing (ASTM G39 style specimens)

* Application of susceptible alloys was being considered at that time

FINAL COMMENTS

- The current standard of testing for SCC (ASTM G47) is not capable of detecting the HEAC

- Necessity to:

  - Development of HEAC test standartization

  - Development of alloy classification - resistance to HEAC (similar to ASTM G64 ranking)

THANK YOU

embraer.com

AFRL-FAA TIM on EAC/SCC of High Strength 7000 Series Aluminum Alloys

Lockheed Martin Experiences and Efforts – EAC/SCC of 7000 Series Alloys

LOCKHEED MARTIN

J B Yates, Principal Engineer

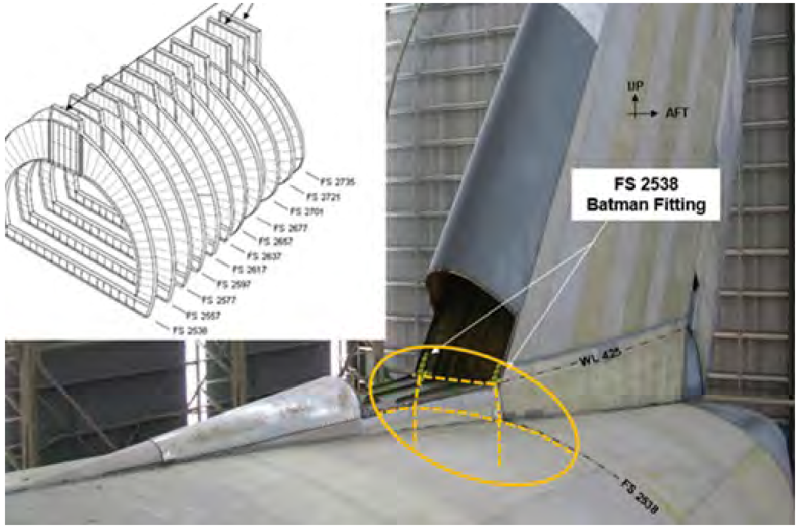
Outline

1. C-5 Experience
   - 7075-T6 & 7049-T73 Die Forgings
   - 7085-T7452
2. F-35 Experience
   - Full Scale Durability Test Teardown Findings
   - EASA 2018-04R2
   - USAF Airworthiness Advisory AA-21-03
   - Engineering Investigation EI-2296
   - Fleet Findings
   - NDI Findings
   - Next Steps
   - Recommendations

C-5 Experience: Batman Fitting

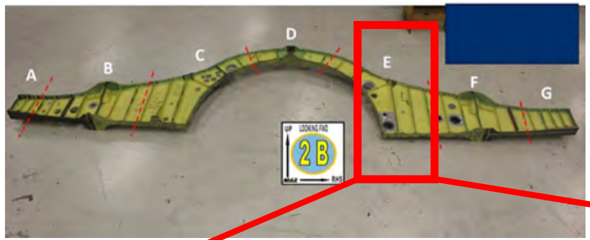
- **Original FS 2538 Fittings Under Vertical Tail Were Found to be Cracked Due to Fatigue on Multiple Aircraft Resulting in Reanalysis and Decision to Replace Existing Fittings (7075-T6 and 7049-T73) with Redesigned Fittings of 7085-T7452 Die Forgings**

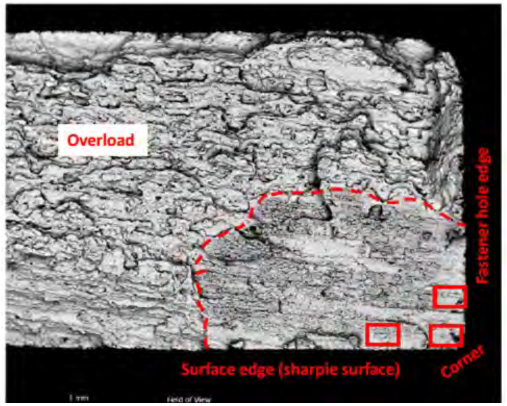
- **Cracking was then found on some of the new 7085 fittings at new locations**
  - **AFRL Characterized the dominant factor for the cracking of the fittings as being due to “high installation stress resulting from shimming anomalies during installation”**
  - **Gaps and permanent deformation were observed after fastener removal**
  - **“Cracking both at the transition radius and at interference fit fasteners is intergranular at sub-grain boundaries. The fracture surface morphologies are consistent with fractures induced in 7085 material during hot humid conditions at very high applied stresses.”**

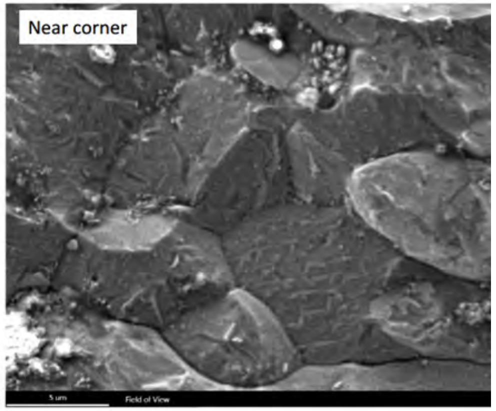


F-35 Durability Test Teardown Findings

- **60 findings were noted <u>during teardown</u> that grew parallel to the major loading of the part**
  - *NONE of these findings were detected during the test or resulted in a test stoppage.*
  - *13 were detected by Bolt Hole Eddy Current but not Eddy Current Surface Scan*
- **Fractographic analysis was conducted on 10 of the findings**
  - *Fractography revealed intergranular cracking on 8 of these findings and fatigue on the remaining 2 findings.*
  - *Some cracks appear to be clustered in a region of the part while others are widely distributed*
  - *All cracks to date are in S-L or S-T orientation*







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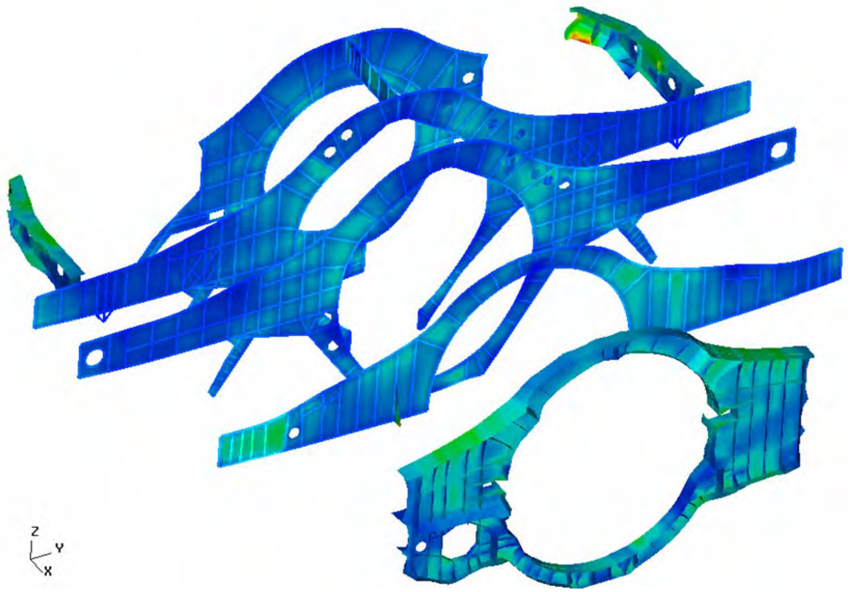
Mitigation Using EASA Guidance and Analysis

- **EASA issued a Safety Information Bulletin (EASA SIB 2018-04R2 13SEP2018) warning of Environmentally Assisted Cracking in certain aluminum alloys (newer 7000 series alloys with high Zinc to Magnesium ratios – including 7085) due to reports of brittle cracking in aircraft components**
  - *Concluded that at this time this concern is* ***<u>not an unsafe condition</u>***
  - *Recommended more stringent accelerated SCC/EAC Testing Conditions*
    - **85%TYS / 70deg C / 85%RH / 100 Days**
- **USAF Released Airworthiness Advisory AA-21-03**
  - *7085-T7452 was tested by AFRL – one invalid failure in the threads at 110 days, 4 remaining coupons* ***survived*** *to end of test at 183 days*
  - *Survived beyond 100 days required by EASA SIB 2018-04R2*
  - *Sustained Stresses are to be kept below 35 ksi*
  - *Survey of F-35 AVFEM Sustained Loads in Max Principal Direction showed that most stress levels remain below 10 ksi. A small number of locations had sustained stresses of just under 20 ksi*
  - *Stresses for press-fit and ForceMate bushings were examined and determined to be below MMPDS SCC Threshold*
  - *A further review using more refined sector FEMs is in work to analyze the sustained stress in the ST & SL orientations – Expected to be lower than the max principal orientation*



(up) z
Y(rh)
X
(aft)

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Engineering Investigation EI-2296

- EI-2296 was conducted to investigate the cause(s) of the Intergranular Cracking Observed in the Full-Scale Durability Test Teardown.
  - Two Phases of testing were conducted, each lasting 1 year and testing a variety of configurations (surface treatments, coatings, faying surface sealants, interference levels and coating thicknesses).
  - Two Plates (7050 and 7085) were fastened together with 3 interference fit fasteners. The interference level was selected to produce ~40 ksi stress
  - These coupons were exposed to 85% RH at 70C or 50C for one year and inspected for cracking at monthly intervals
- The results indicated that the cracking was sensitive to interference level and temperature and that it initiated at the faying surface.
  - A test series which omitted faying surface sealant, and which included fuel tank coating exhibited least cracking/longest duration without cracks
- Additional testing is currently in planning

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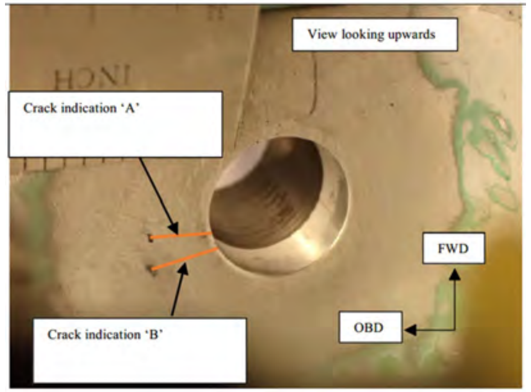
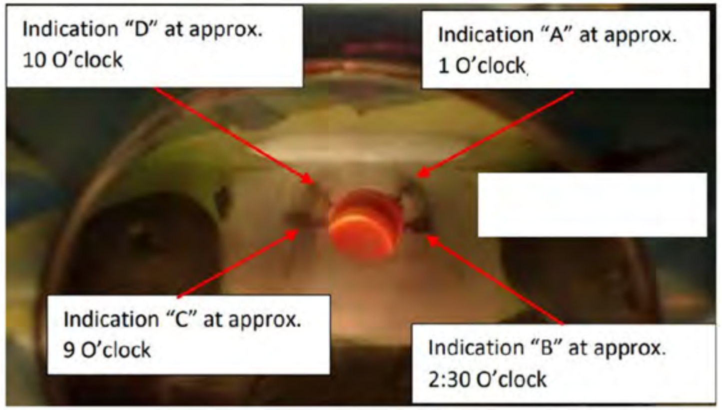
Fleet Findings

- **Suspected Intergranular Cracking has been recently found on multiple fielded aircraft**
  - These findings are generally too large to remove within standard rework limits
  - The findings are oriented in the same direction as the predominant loading rather than perpendicular to it
  - Some holes have multiple crack indications adjacent to each other
- **One finding required an engineered repair and allowed for the excision of the finding**
  - Fractographic examination proved that this indication was, in fact, intergranular cracking
  - Because multiple attempts to remove the indication had been performed prior to excision, the initiation site was not available for investigation





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NDI Findings

- A review of 7085 NDI findings for machined parts revealed a number of small indications on a fraction of the parts which were readily removed by light blending
- These NDI findings were small linear indications in the ST and SL direction on curved machined surfaces.
- Since these indications occurred on only a subset of the parts, it may indicate a relationship to the chemistry or processing of the material
- This is a recent finding, and more analysis is needed to understand if it is related to the HEAC/IGC issue

Technical Solution: Potential Next Steps

- **Continued Collection of Data from Fleet and Manufacturing Inspections**
- **Identify and Quantify Sources of Stress**
  - *Residual Stress*
  - *Assembly Stress*
  - *Cold Work*
- **Crack Arrest Analysis**
  - *No fatigue growth observed on FSDT or Fleet findings*
  - *What does observed crack length tell us about* K_{ISCC}/K_{IC}*?*
- **Risk Analysis**
  - *How many holes inspected? vs How many IG Cracking Findings?*
  - *How many locations splice load in ST direction?*

Recommendations

- *Additional Screening/Characterization Testing for New Aluminum Alloys*
    - *Traditional SCC Testing did not predict the HEAC/IGC Sensitivity Exhibited by 7085-T7452*
- *Testing for Varying Levels of Humidity/Temperature with Increased Resolution*
    - *Cracking exhibited on Full Scale Durability Tests did not require exposure to typical operation environments*

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AFRL-FAA Technical Interchange Meeting (TIM) on Environmentally Assisted Cracking (EAC) / Stress Corrosion Cracking (SCC) of High-Strength 7000 Series Aluminum Alloys

November 5-6, 2024 in Dayton, OH

Ryan Davis, Wenping Zhang

ARCONIC

Bounding the Problem and Key Influential Factors

How has your organization bounded the problem definition of unexpected cracking in 7XXX aluminum alloys in service? If possible, provide a brief explanation and examples in a pre-competitive format.

Arconic understanding is that it is a particular type of environmental assisted cracking (“EAC”) known as stress-corrosion cracking (“SCC”) caused by high sustained tensile stress in the normal operating environment of certain 7xxx alloy/tempers. SCC has been a known potential risk in 7xxx series aluminum alloys for more than 70 years.

What key influencing factors are suspected for the damage mechanism(s) identified above (e.g. humidity, temperature, steady-state stress, other)?

Certain 7xxx alloys/tempers, high sustained tensile stress, environmental conditions (humidity, temperature, etc.)

ARCONIC

Perceived Critical Questions and Potential Solutions

What are the 3-5 most critical questions that you think need to be answered?

1. What mechanism(s) are most influential in development of SCC in this specific environmental condition?
2. Why are some materials (alloy/temper) more susceptible to this type of cracking than others?
3. What levers can be utilized to control the behavior of SCC (EAC) phenomena?
4. What is the right test to assess the susceptibility of 7xxx to this type of cracking? How to judge if a test method is good?
5. Will a new class of 7xxx plate products be required by OEMs or will closely monitored existing products be sufficient?

What are your hypotheses about the problem and potential solutions to that problem?

Problem Statement: literature has shown that 7xxx series alloys/tempers under high sustained tensile stresses operating in normal environmental conditions (presence of moisture, typical operating temperature, etc.) can be susceptible to stress corrosion cracking (SCC).

Potential Solutions: there are three elements to the SCC problem: materials, sustained tensile stress, and environment. Selecting a 7xxx/temper with adequate SCC resistance and adherence to common practices in design to reduce the sustained tensile stress to be within the material capability can be potential solutions to this problem.

Participant Resourcing and Crowdsourcing Research

Does your organization have the resources to answer the 3-5 questions? Arconic has technical resources dependent on Supplier/Customer agreements.

If so, what is the timeline to address the 3-5 questions?

Will this information be shared with the community?

No, Arconic would consider any findings its own intellectual property.

How would the community validate your work so it can be used to the greatest impact?

No comment

Do you foresee any significant challenges with translating research results into practical applications (e.g. predictive modeling or the establishment of threshold criteria)?

- Legal liability would need to be managed through appropriate Supplier/Customer contracts
- Confidential information would need to managed through NDAs, and other research/development agreements

Standardized Testing, Alloy Development, and Collaboration

What suggestions does your organization have for a community-wide standardized test to address the cracking problem, and could it be used as part of the material qualification/certification process?

Arconic recognizes the adopted industry testing standards of ASTM for specific aerospace products. Arconic is open to participating in the balloting and approval process that leads to industry-wide agreement of a new test standard. A 100+ day test is likely not realistic/feasible for lot release, but it's reasonable to see this becoming a criteria for material qualification.

Is there a suggested path forward for new alloy development?

Depends on OEM interests for a new product and willingness to partner in the cost of development for a specific metallic solution.

Do you have suggestions for preferred community-wide collaboration mechanisms to share research progress or engineering solutions?

No comment

ARCONIC

EAC/SCC of 7xxx aluminum alloys in high humidity environments

Presentation for AFRL/FAA Joint Symposium
Dayton, Ohio, USA
November 5, 2024

Constellium

Introduction

- Constellium has been actively addressing the topic of EAC/SCC of 7xxx alloys as described in EASA SIB 2018-04 for many years

- Our understanding of this topic has been informed by:
  - Extensive testing, characterization, and analysis at our world renowned R&D center (C-TEC)
  - In depth analysis of the open scientific literature
  - Partnerships with best in class academic laboratories (e.g. Max Planck Institute (MPIE), Brunel University, …)
  - Confidential customer discussions

- As a metal supplier we have no direct expertise regarding the stresses or environments that our materials are exposed to

Problem Definition
Terminology related to Environmentally Assisted Cracking

- Environmentally Assisted Cracking is generally used in the industry as a generic term covering many phenomena, themselves not fully distinct from each other

- SCC cracks for 7xxx aluminum propagate via a hydrogen embrittlement mechanism in both humid air and salt water.

- Corrosion reactions at the crack tip generate hydrogen atoms that can diffuse into the material and embrittle it ahead of the crack.

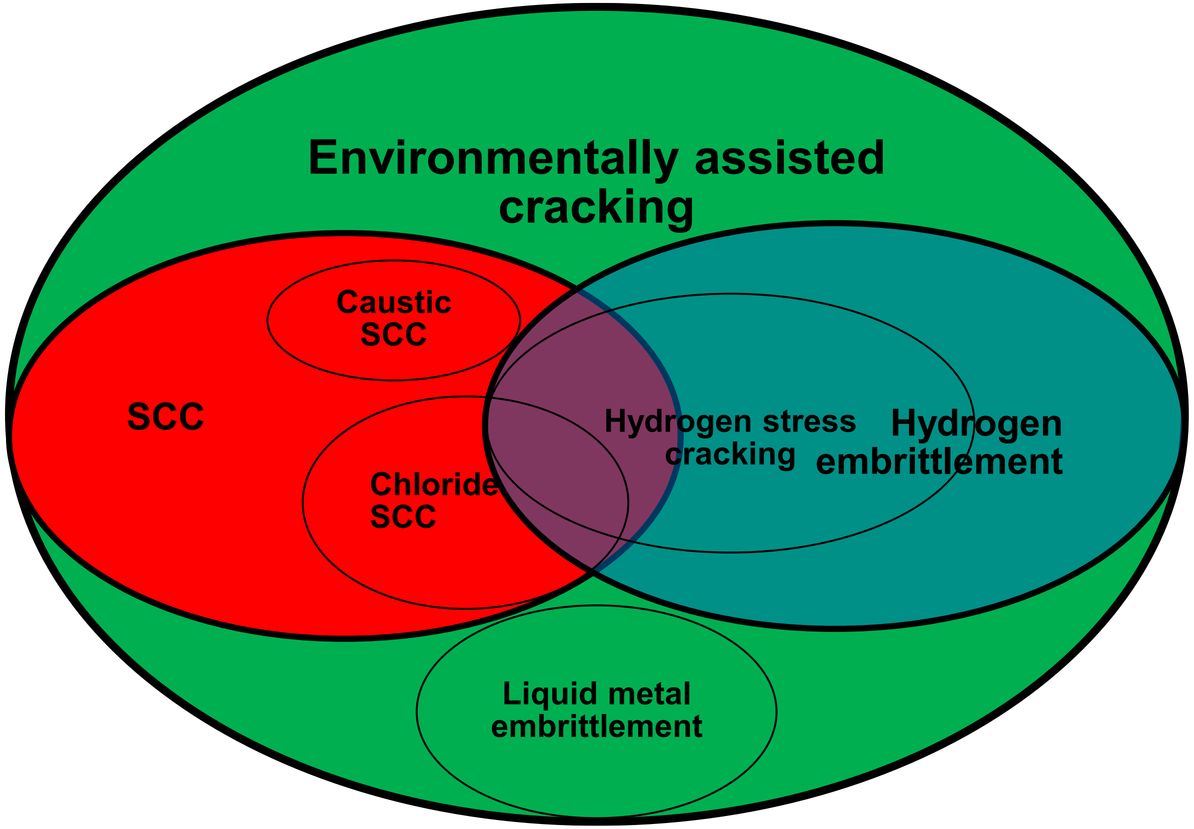

Diagram based on definitions in ASTM G193: Standard terminology and acronyms relating to corrosion

Problem Definition

Constellium in service knowledge limited to content of EASA bulletin and bilateral exchanges

SIB 2018-04R2 Description

- "…caused by hydrogen embrittlement along the grain boundaries…"
- "…brittle cracking…"
- "…usually propagate in a plane perpendicular to the short transverse (ST) direction."
- "Predominantly intergranular fracture path with little or no evidence of ductile decohesion"
- "…decrease of toughness but in absence of an obvious corrosion reaction…"

EAC test

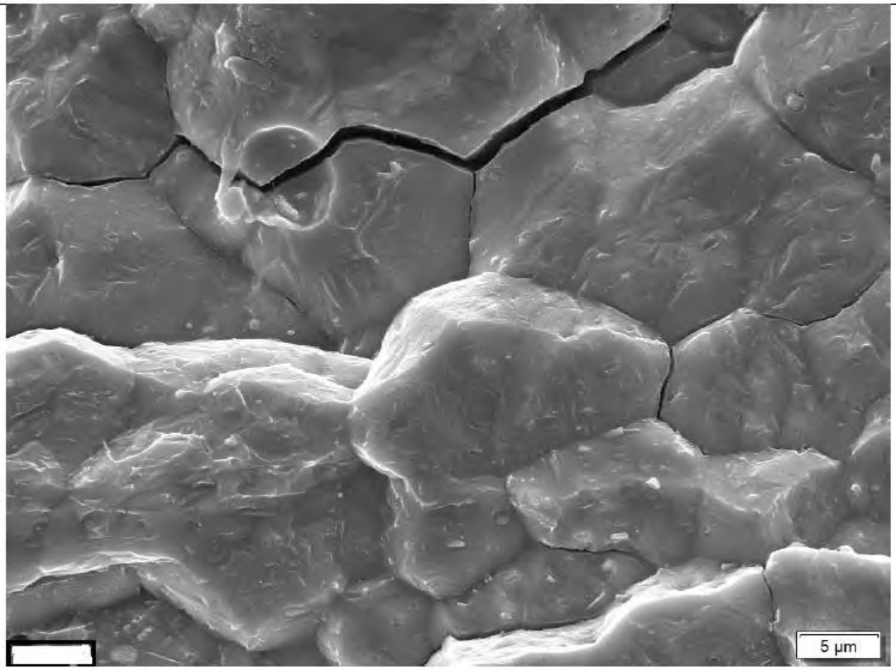

Figure 5 – Typical EAC fracture surface

Problem Definition
Indistinguishable from reported in service SCC

- Similar fracture surfaces to the “typical EAC fracture surface” have been observed in-service for 7XXX alloys and attributed to SCC

- Brittle, intergranular fracture in a plane perpendicular to the ST direction

- No “obvious” corrosion visible

<u>Selected references stating that in-service SCC often occurs without any visible macroscopic corrosion</u>

1. NASA MSFC Spec 522B (NASA, 1987):
2. Wallace, Hoeppner, & Kandachar, <u>AGARD Corrosion Handbook</u>, volume 1, 1985
3. Gruhl, “Stress Corrosion Cracking of High Strength Aluminium Alloys,”1984 :
4. (Stress Corrosion Cracking) in Metals Handbook: Failure Analysis and Prevention, volume 11
5. T. D. Burleigh, Corrosion vol. 47, No. 2, (1991)

In-service SCC failure of 7075-T6

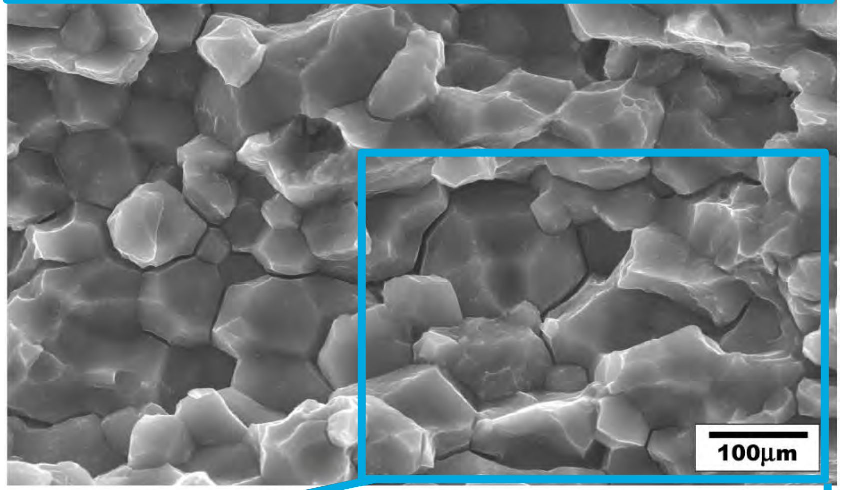

Fig. 7 Clearly intergranular SCC fracture surface: SEM fractograph from a die-forged 7075-T6 aluminium alloy engine truss mount

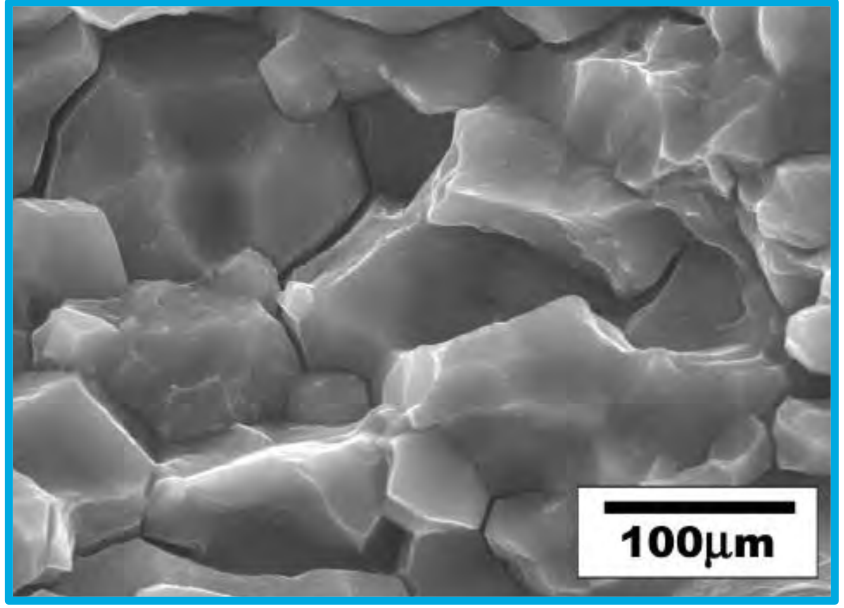

Image from: R.J.H. Wanhill, R.T. Byrnes, and C.L. Smith, <u>Stress Corrosion Cracking in Aerospace Vehicles</u>, National Aerospace Laboratory (NLR) Report Number NLR-TP-2010-538, 2010.

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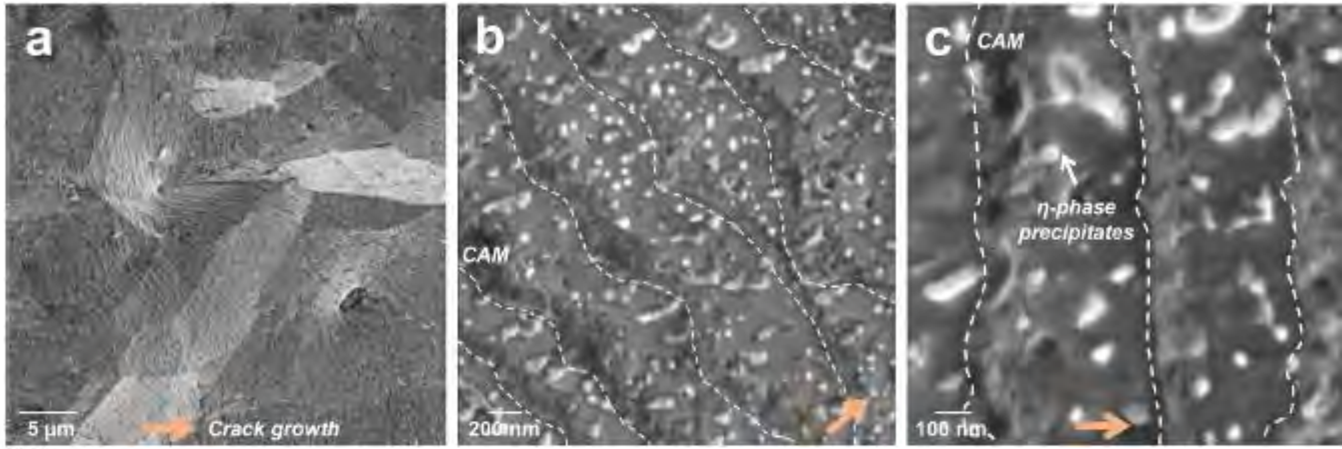
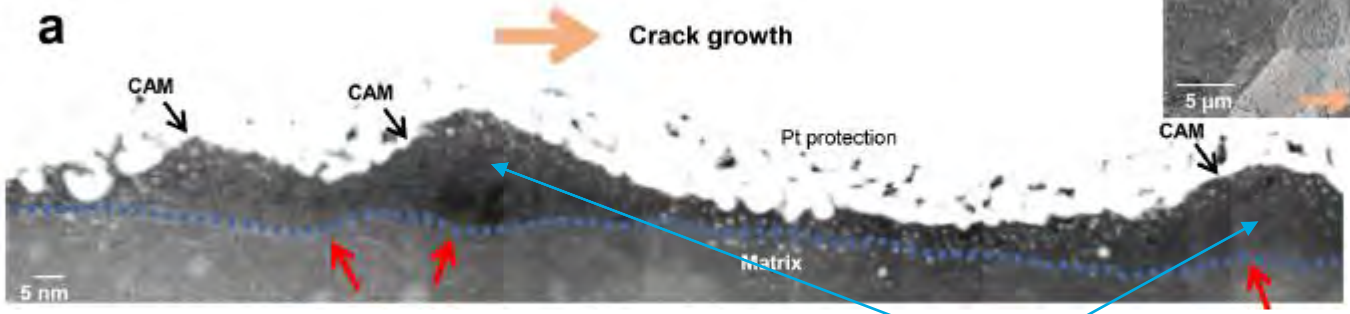
Problem Definition
Corrosion Products in CAMs on fracture surfaces

SEM images showing CAM's on SCC fracture surface of a 7xxx alloy tested at 70°C and 85% R.H. using a double cantilever beam specimen



M. L. Freixes et al., "Crack arrest markings in stress corrosion cracking of 7xxx aluminium alloys: Insights into active hydrogen embrittlement mechanisms," *Scripta Materialia,* 237 (2023) 115690

TEM High-angle annular dark field micrograph showing a cross section view of the CAMs



Oxide strips, typically 150-500 nm apart, 20-30 deep

The combination of oxidation of aluminum (corrosion) and reduction of water creates the potentially adsorbed hydrogen ions:

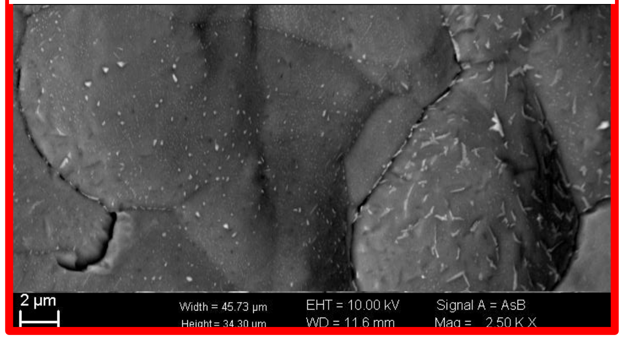
$2Al + 3H_2O \rightarrow Al_2O_3 + 6H^+ + 6e^-$

$H_2O + e^- \rightarrow H_{ads}(c) + OH^-$

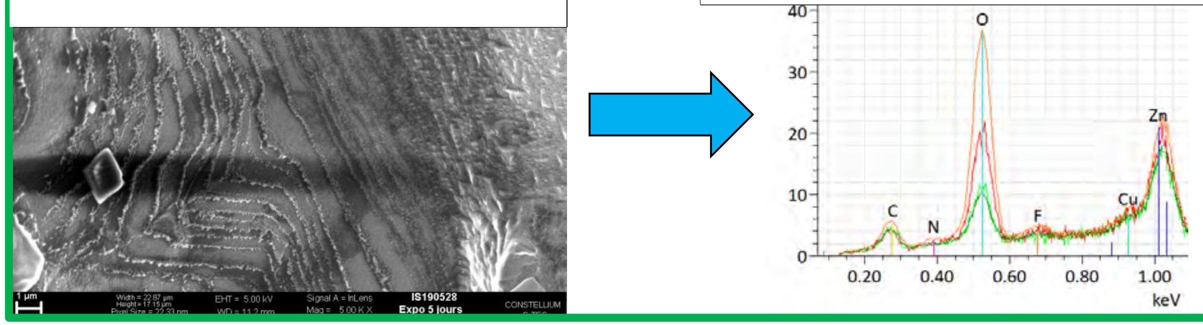
- 7xxx SCC Mechanism: Corrosion/hydrogen generation → Embrittlement → Propagation

Problem Definition
In-Service Stress Corrosion Cracking: Corrosion Products

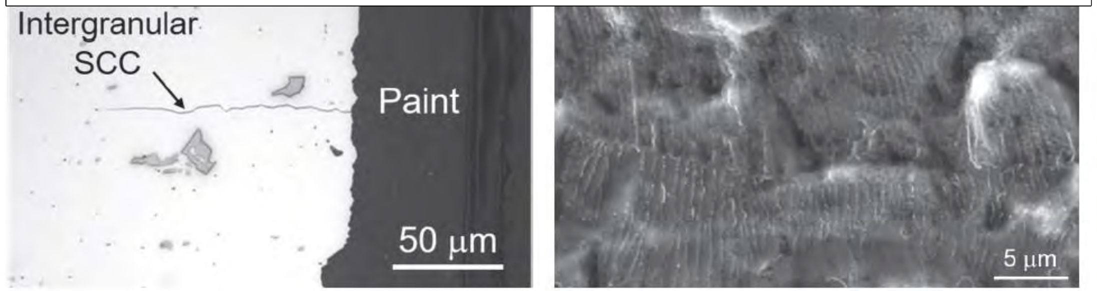
High Accelerating Voltage Images (No "obvious" corrosion visible)



Low Accelerating Voltage Image (Corrosion products visible as crack arrest markings)



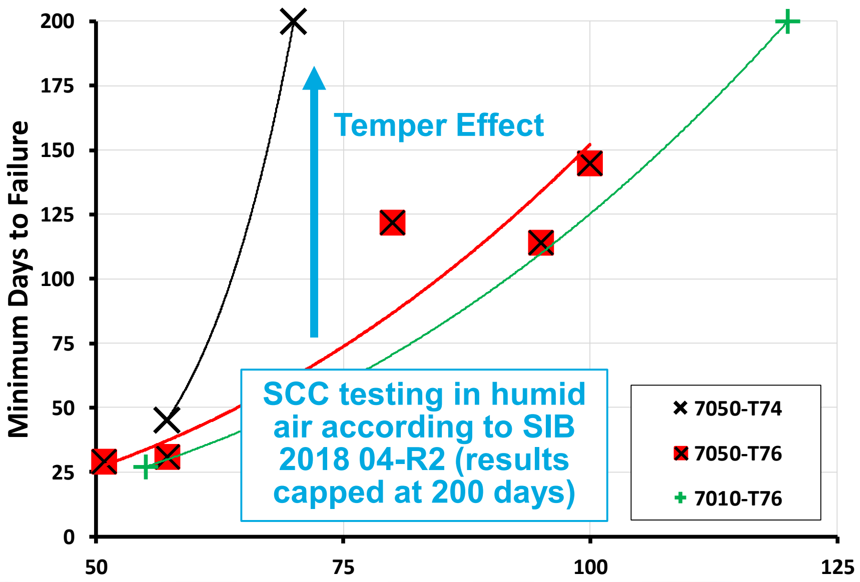
- Low accelerating voltage increases the visibility of corrosion products (oxides/hydroxides) for SCC in humid air
- 7xxx SCC Mechanism: Corrosion/hydrogen generation → Embrittlement → Propagation
- Crack arrest markings are associated with alternating degrees of oxidation
- Crack arrest markings on top of brittle intergranular fracture surface also observed for in-service SCC (e.g. Lynch 2017)
  - *"There was no doubt that the cracks were due to SCC…"*
  - *"…intergranular facets exhibiting crack-arrest markings (CAMs)…"*

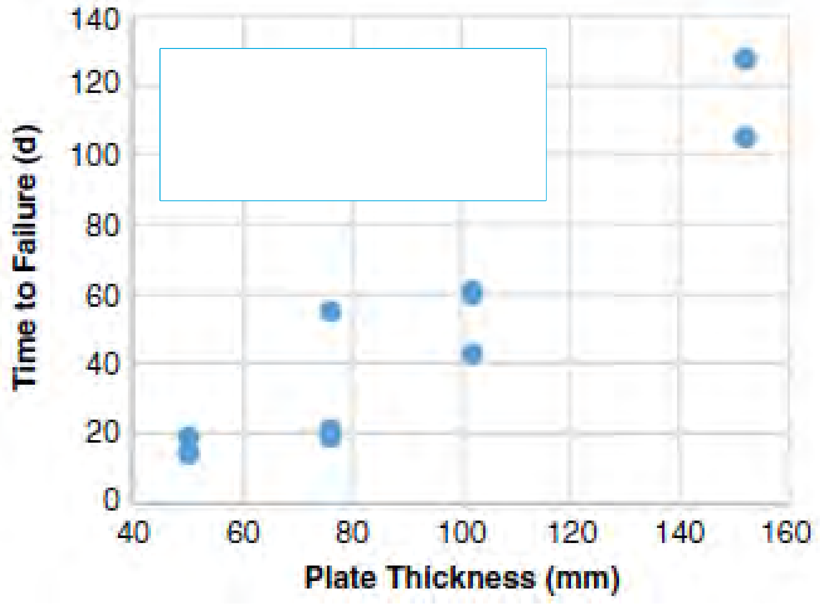


Lynch, S. (2017). Failures of metallic components involving environmental degradation and material-selection issues. *Corrosion Review*.

Key Parameters affecting SCC Resistance
Material Parameters

- The same trends are observed in humid air and in ASTM G44/G47
- SCC resistance of 7xxx alloys is not solely determined by chemical composition, it is determined by a combination of parameters
- Temper: SCC Resistance T73 > T74 > T76 > T79 > T6
- Thinner plates are less resistant and fail faster
  - Flatter grain structure
- Cu content has the largest compositional effect on SCC resistance
  - Especially when over-aged





T. Warner et al., "Effect of Testing Conditions, Gauge, and Temper on Stress Corrosion Cracking of AA7xxx Aluminum Aerospace Plate Alloys," *Corrosion, vol. 79, issue 1, 2023, (35-47)*

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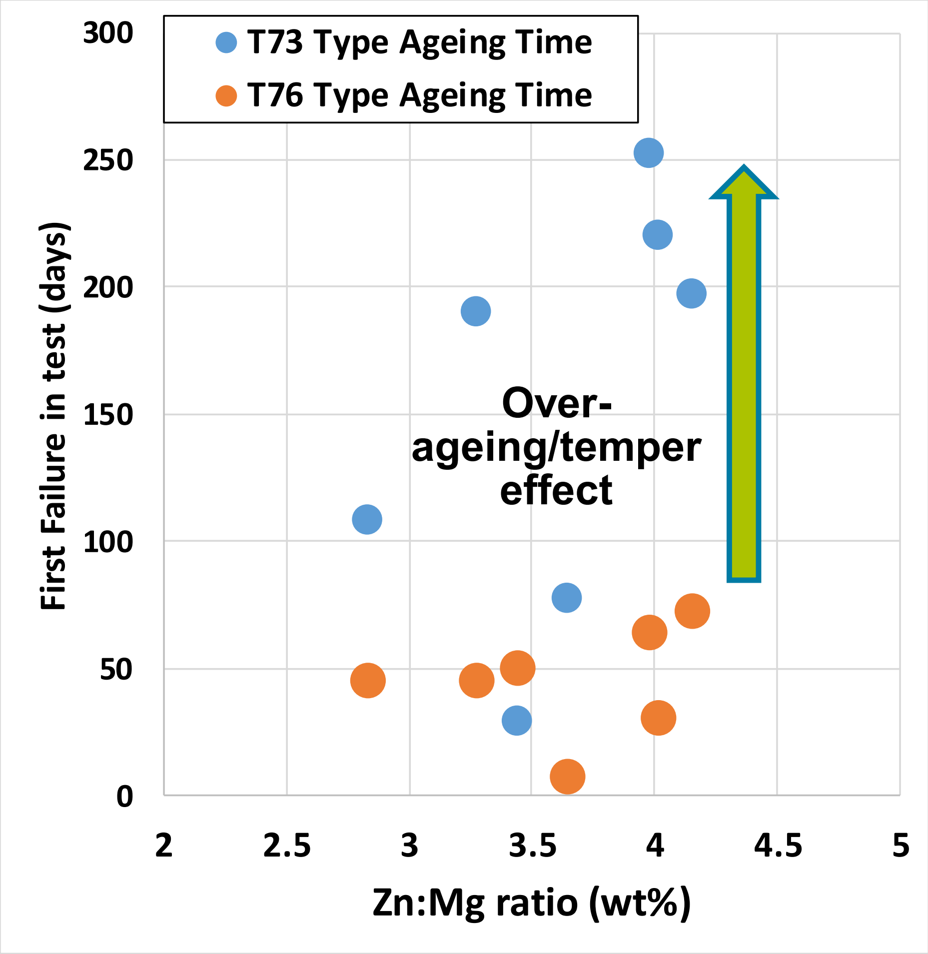
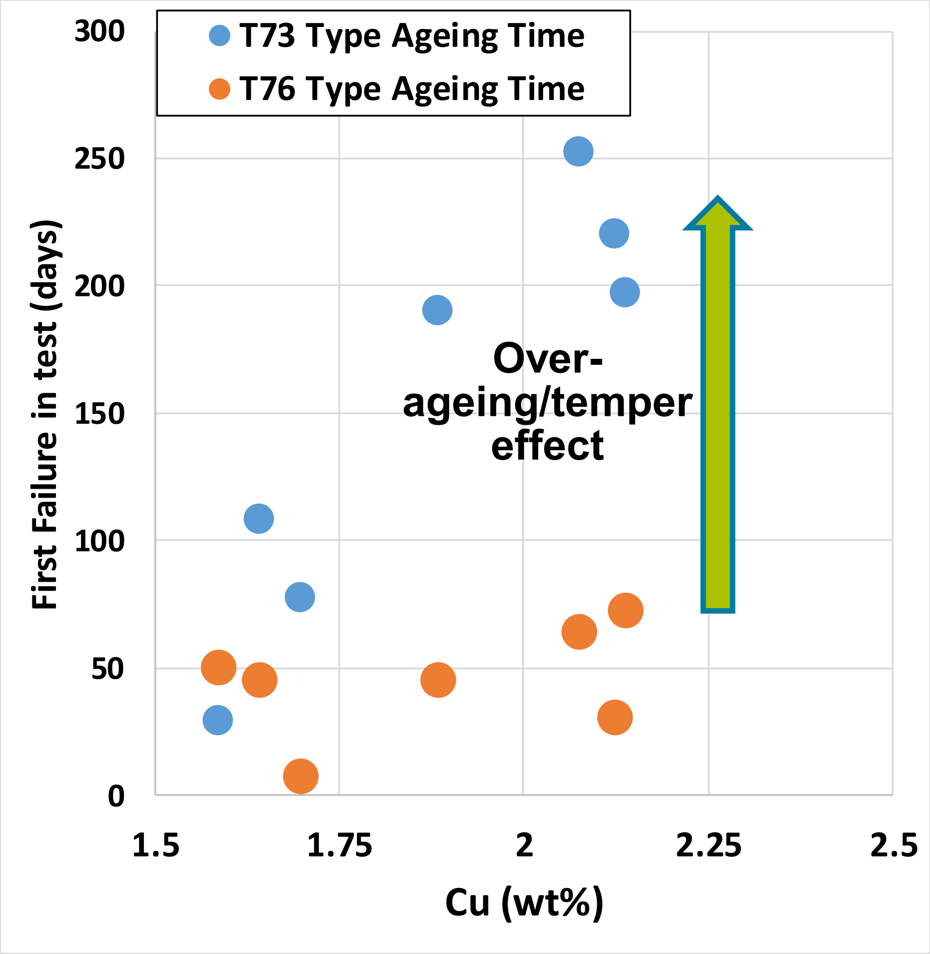
Key Parameters affecting SCC Resistance
Material Parameters

- Over-ageing and Cu content have larger effects than Zn:Mg ratio
  - Same casting and rolling campaign, ageing performed in same furnace for same times
  - Same plate thickness (4 inch / 102 mm)
  - Systematic variation in Zn:Mg and Cu

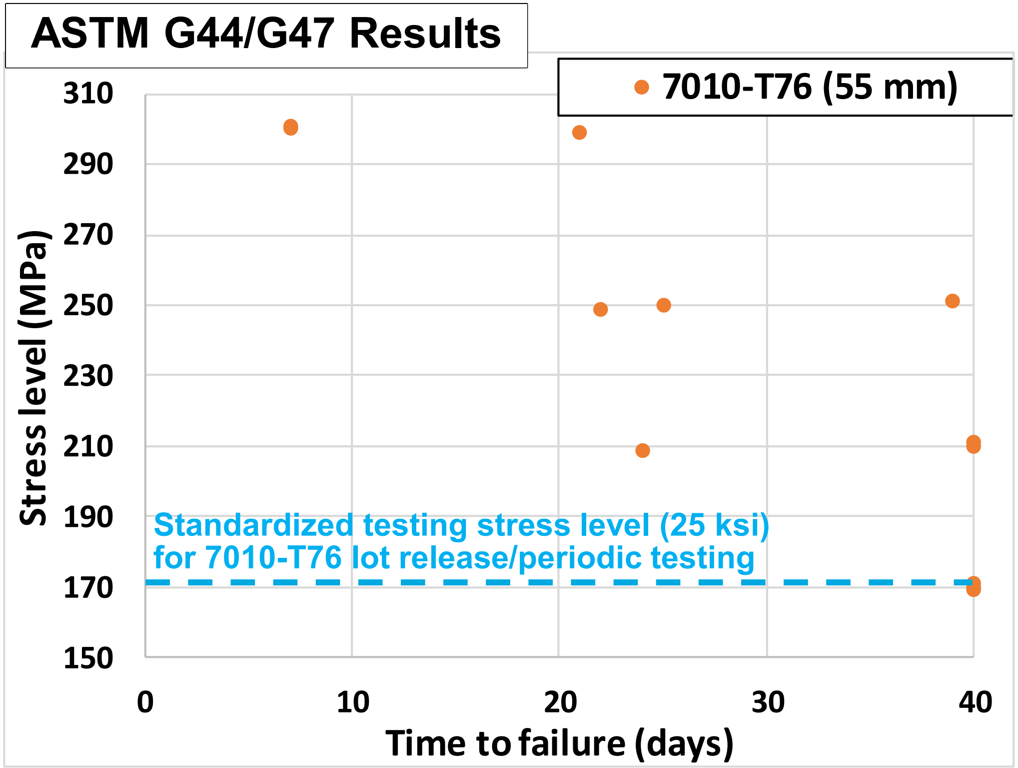




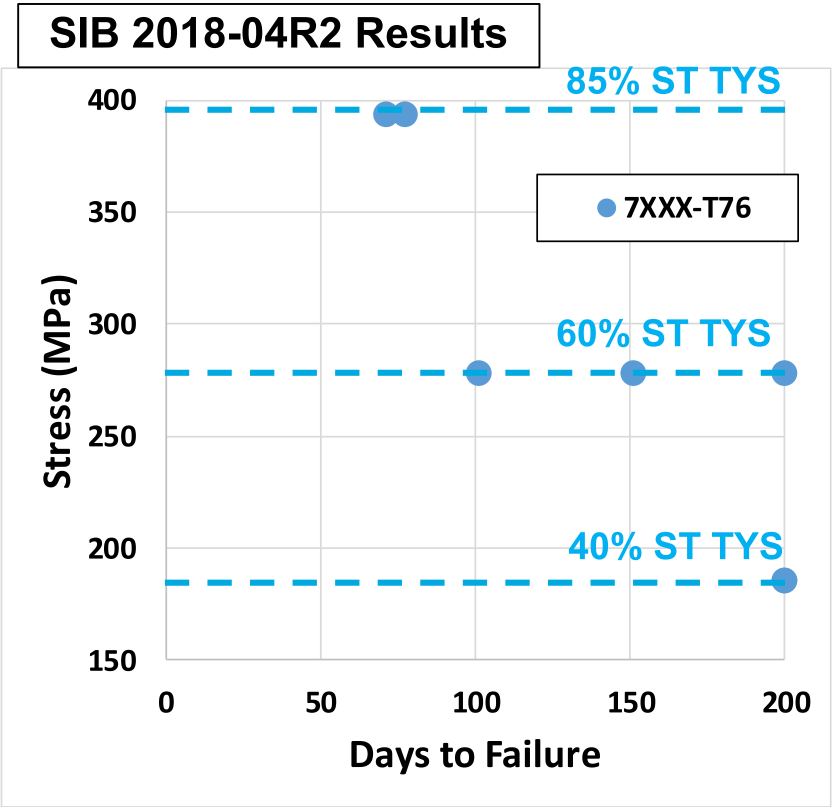
SCC testing in humid air according to SIB 2018 04-R2

Key Parameters affecting SCC Resistance

Testing Parameters: Applied Stress/Sustained Stress



SCC testing in 3.5% NaCl according to ASTM G44/G47.
Results capped at 40 days



SCC testing in humid air according to SIB 2018 04-R1.
Results capped at 200 days

- There are substantial effects of stress on SCC life-time in humid air (SIB 2018 04R1 test) and in 3.5% NaCl (ASTM G44/G47)
- Products show a typical “threshold curve” with stress level
- The “threshold stress” depends on the environment (temperature, humidity, chloride content, etc…)

Key Parameters affecting SCC Resistance
Testing Parameters: Applied Stress/Sustained Stress

ASTM G64 Rating	Applied Stress Capability	Typical 7xxx products in ST direction
A	75% of specified minimum yield strength	T73 tempers
B	50% of specified minimum yield strength	T74 tempers
C	25% of specified minimum yield strength	T76 tempers
D	Fails to meet C rating	T6 tempers

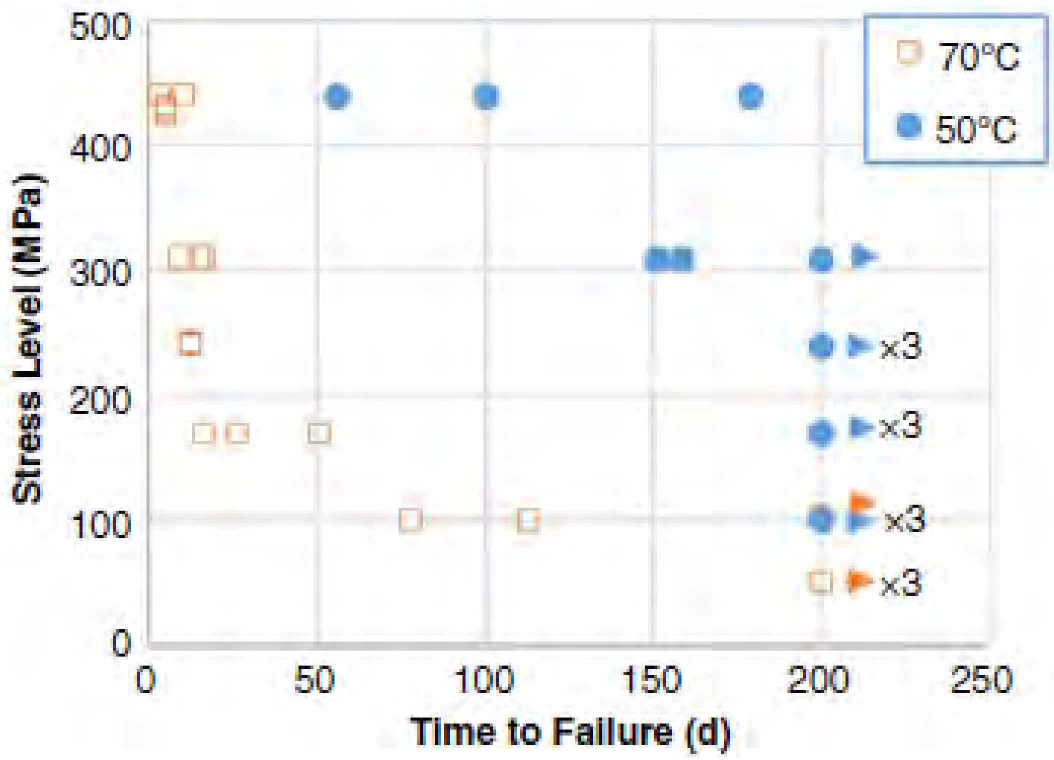
- It is recommended that any standardized test be flexible regarding applied stress to account for the variation in needed SCC resistance
  - Example language from ASTM G47 regarding applied stress: ***"One or more levels as specified or as required to determine comparative stress corrosion resistance"***

ASTM G64 or G47	**SIB 2018-04R2**
Less SCC resistant/higher strength tempers are **tested at lower stress**	Less SCC resistant/higher strength tempers are **tested at higher stress**

Key Parameters affecting SCC Resistance
Testing Parameters: Stress and Temperature

- ISO 7539-1: Corrosion of Metals and Alloys – Stress Corrosion Testing
  - "…it is clear that the **test temperature should be closely controlled and whenever possible this should be selected to correspond to that expected in service**, ...increased temperature is sometimes used to accelerate test results, clearly such an approach must be undertaken with caution."
- NACE/ASTM G31: Standard Guide for Laboratory Immersion Corrosion Testing of Metals
  - "If the test is to be a guide for the selection of a material for a particular purpose, **the limits of the controlling factors in service shall be determined**. These factors include oxygen concentration, **temperature**, rate of flow, pH value, composition…"
- The test temperature should correspond to the expected maximum in-service temperature
  - Avoiding activation of other mechanisms / rate determining steps

E.g. NASA MSFC-STD-3029A describes a test for "Stress Corrosion Susceptibility" in humid air" using 97% R.H. at 38°C (100°F)



SCC testing in humid air according to SIB 2018 04-R2. Results capped at 200 days

T. Warner et al., "Effect of Testing Conditions, Gauge, and Temper on Stress Corrosion Cracking of AA7xxx Aluminum Aerospace Plate Alloys," *Corrosion, vol. 79, issue 1, 2023, (35-47)*

Critical Questions for the Aerospace Industry

- What are the actual temperature and sustained stress levels that 7xxx aluminum products are exposed to during service?

- Is the level of sustained tensile stress consistent with the SCC resistance of the material implied by its SCC rating (ASTM G64)?

- What is the most representative testing method to measure relative SCC resistance under humid conditions?
  - Actual in-service temperatures and sustained tensile stress should be accounted for in the test method
  - Crack rate could also be relevant if there is a pre-existing crack (e.g. double cantilever beam specimens)

Suggested Next Steps for Collaboration

- Could be divided into several topics such as:
  - Understanding of underlying mechanisms
    - Active participants: academic partners and industry
    - Co-funded PhDs?
  - Development of a standardized testing practice
    - Active participants: industry, standardization organizations, (academic partners)
    - Co-funded activity within standardization organizations?
  - Development of design / manufacturing / materials selection rules to avoid future cracking issues
    - Active participants: industry, standardization/certification organizations

For more information about stress corrosion cracking in humid air, please see Constellium's presentation to MMPDS (September 2019), our presentation to ICAA (October 2020), our presentation to Aeromat (May 2021), and our presentation to ICAA (June 2024)

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Stress corrosion cracks propagate by hydrogen embrittlement in 7xxx aluminum alloys

SIB 2018-04R1: "…caused by hydrogen embrittlement along the grain boundaries…"

- In 7xxx aluminum alloys, crack propagation during SCC is widely accepted in the scientific literature as being due to hydrogen embrittlement
  - The hydrogen is supplied via aluminum oxidation by H_2O
  - Selected corrosion review papers as an example:

T. D. Burleigh, Corrosion vol. 47, No. 2, (1991) p. 97

"…the proposed mechanism of SCC depends on the alloy system in question: anodic dissolution is favored by most researchers in the 2xxx alloys (Al-Cu and Al-Cu-Li), while hydrogen-induced cracking is favored by most researchers in the 7xxx and 5xxx alloys"

S. P. Knight et al., Corrosion Science vol. 98 (2015) p. 51

"SCC in 7xxx Al alloys is generally attributed to the embrittling effects of hydrogen, although the precise mechanisms are still being debated"

N. Ben Ali et al., Scripta Materialia vol. 65 (2011) p. 210

"The fracture of high-strength aluminum alloys, especially via stress corrosion cracking and corrosion fatigue, often involves hydrogen"

S. Lynch, Corrosion Review vol. 30 (2012), p. 72

"Mechanisms of SCC based on the effects of hydrogen on deformation and fracture are widely accepted for many materials, e.g., high-strength steels, nickel alloys, titanium alloys, aluminium alloys, and magnesium alloys,"

The hydrogen ions are generated by a corrosion reaction

SIB 2018-04R1: "…caused by hydrogen embrittlement along the grain boundaries…"

"…absence of an obvious corrosion reaction…"

- Unlike steels, aluminum alloys do not suffer from hydrogen embrittlement when exposed to (dry) hydrogen gas, even under very high pressures
- The combination of oxidation of aluminum (corrosion) and reduction of water creates the potentially adsorbed hydrogen ions

J. R. Scully, G. A. Young Jr., and S. W. Smith, "Hydrogen embrittlement of aluminum and aluminum-based alloys," in Gaseous hydrogen embrittlement of materials in energy technologies, vol. 1, Philadelphia: Woodhead Publishing, 2012, pp. 707–768.

"During Al oxidation in humid air the following reaction sequence occurs spontaneously or naturally. First aluminum is oxidized in water vapor to form oxide according to the following half cell reaction:"

$$2Al + 3H_2O \rightarrow Al_2O_3 + 6H^+ + 6e^-$$

"…In neutral waters, the following reaction occurs…"

$$H_2O + e^- \rightarrow H_{ads}(c) + OH^-$$

The hydrogen ions are generated by a corrosion reaction

SIB 2018-04R1: "…absence of an obvious corrosion reaction…"

- NASA MSFC Spec 522B (NASA, 1987):
  - "Service failures due to stress corrosion are frequently encountered for which the surface of the failed parts are **not visibly corroded** in a general sense."
- Wallace, Hoeppner, & Kandachar, AGARD Corrosion Handbook, volume 1, 1985
  - "Stress corrosion is a particularly insidious form of corrosion since it will often occur with **little or no visual evidence of surface corrosion** such as surface discolouration **or the build up of noticeable corrosion products**."
- Gruhl, "Stress Corrosion Cracking of High Strength Aluminium Alloys,"1984 :
  - "The real SCC in which frequently **without the appearance of any visible corrosion attack**, a discontinuous spontaneous crack formation occurs."
- (Stress Corrosion Cracking) in Metals Handbook: Failure Analysis and Prevention, volume 11
  - "However, the presence of staining or corrosion products on the fracture surface is by no means positive proof of SCC. **Some SCC fractures are not stained or discolored**, especially in materials with good corrosion resistance; in addition, many fractures become corroded before inspection can be accomplished."
- T. D. Burleigh, Corrosion vol. 47, No. 2, (1991)
  - "**During SCC, the aluminum alloy's surface often appears almost corrosion-free**, …although outwardly a structure might appear uncorroded, fine cracks could cause it to be near failure."

KAISER ALUMINUM

ENVIRONMENTALLY ASSISTED CRACKING

NOVEMBER 5 6, 2024
DAYTON, OH

EASA SIB 2018-04R2

EASA SIB No.: 2018-04R2

EASA European Union Aviation Safety Agency

Safety Information Bulletin

Airworthiness

SIB No.: 2018-04R2

Issued: 04 March 2021

Subject: **Environmentally Assisted Cracking in certain Aluminium Alloys**

Revision:
This SIB revises EASA SIB 2018-04R1 dated 13 September 2018.

Ref. Publications:
None.

Applicability:
Type Certificate (TC) holders, Supplemental Type Certificate holders, equipment manufacturers, maintenance organisations, production organisations and aluminium alloy producers.

Description:
EASA received reports of brittle cracking of aluminium alloy components. Additional investigation of some new generation 7xxx series alloys has shown that these have a sensitivity to a phenomenon known as environmentally assisted cracking (EAC), when subject to certain conditions in the normal operating environment. The type of EAC encountered appears to be caused by hydrogen embrittlement along the grain boundaries, leading to crack initiation and subsequent propagation. These cracks typically start from holes or other areas of stress concentration and usually propagate in a plane perpendicular to the short transverse (ST) direction. This phenomenon has been linked to the chemical composition of the alloy, notably a high zinc/magnesium ratio, combined with low copper content. Brittle fractures have been reproduced under laboratory environment and cracking has proven to be driven by time exposure (ageing) and is not fatigue related, although further crack propagation under operative loads cannot be excluded.

EASA SIB No.: 2018-04R2

with loss of material accompanied with findings of active corrosion like pitting or attack of grain boundaries (see Appendix 1 of this SIB, Figure 6).

Sensitivity to this form of EAC has been confirmed for alloys 7037, 7040 (see Note 2 of this SIB), 7055, 7085, 7099, 7140 (see Note 2 of this SIB), and 7449. Other alloys with similar compositions might also be affected. The material temper (i.e. the specified heat treatment and additional processing such as ageing and stress relief by stretching) and product form can also influence resistance to EAC.

Note 2: Aluminium alloys 7040 and 7140 have been found to be sensitive to this form of EAC in T7651 temper, whereas the T7451 temper of these alloys has been observed to demonstrate acceptable behaviour in applications of some TC holders. Other tempers commonly used with 7040 alloys have, thus far, not exhibited sensitivity to EAC.

Occurrences of this form of EAC cannot be excluded in service and, if not detected, could lead to crack propagation, possibly resulting in reduced structural integrity. For specific designs that have already been identified, mandatory inspections and corrective actions have been initiated and further mandatory actions for other specific designs may follow.

EASA issued SIB 2018-04 to raise awareness, in all sectors of the industry, concerning this EAC phenomenon of these types of aluminium alloys. That SIB was revised to add aluminium alloy 7140 and to provide a generic test method that can be used to identify material susceptibility to this form of EAC. The current revision of this SIB provides further information on the aluminium alloy 7140 in T7451 temper.

At this time, the safety concern described in this SIB is not considered to be an unsafe condition that would warrant Airworthiness Directive (AD) action under Regulation (EU) 748/2012, Part 21.A.3B.

EASA SIB 2018-04R2: Kaiser Materials

Any reports of 7099 HEAC issues from customers?

- No reports from any customers for known 7099-T7651 or 7099-T7451
- No reports of any Kaiser specific products of known HEAC issues

EASA SIB2018-04R2: Test Conditions

Test Condition

- Geometry: ASTM G49/E8 round smooth bar along ST orientation
- ASTM G49 Loading fixture
- Constant Load/Displacement per ASTM G49
- Load to 85% ST, YTS per ASTM G49 loading methodology
- RH=85%±5% and Temp = 70°C±1°C
- Duration min 100 days, can test out to 200 days

Valid test

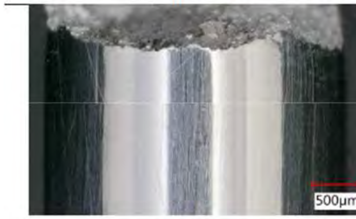


Figure 1 – Round smooth bar: not corroded

Non-valid test due to condensation

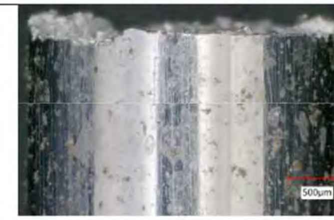


Figure 2 – Round smooth bar: corroded

Test Evaluation

- Cracking along GB without corrosion attack or oxidation products on fracture surface
- Cracking along GB at 50x
- Retest if:
  - condensation on sample, pitting, corrosion, intergranular failure (6000x) with no evidence of ductile decohesion

EASA SIB2018-04R2: Kaiser Testing

EASA SIB 2018-04 R2 Conditions

- EAC requires
  + susceptible material alloy
    + sustained stress in the ST direction
      + ageing in a typical environment

Alloy	Cu	Mg	Zn
7037	0.6-1.1	1.3-2.1	7.8-9.0
7040	1.5-2.3	1.7-2.4	5.7-6.7
7140	1.3-2.3	1.5-2.4	6.2-7.0
7449	1.4-2.1	1.8-2.7	7.5-8.7
7055	2.0-2.6	1.8-2.3	7.6-8.4
7085	1.3-2.0	1.2-1.8	7.0-8.0
7099	1.4-2.1	1.6-2.3	7.4-8.4

Kaiser Testing Capabilities

Discussion

KAISER ALUMINUM

www.KaiserAluminum.com

ARFL-FAA TIM on HEAC in 7xxx-Series Aluminum Alloys

Justin Lamb PhD
Director of Metallurgy and R&D

Dayton, OH
5 November 2024

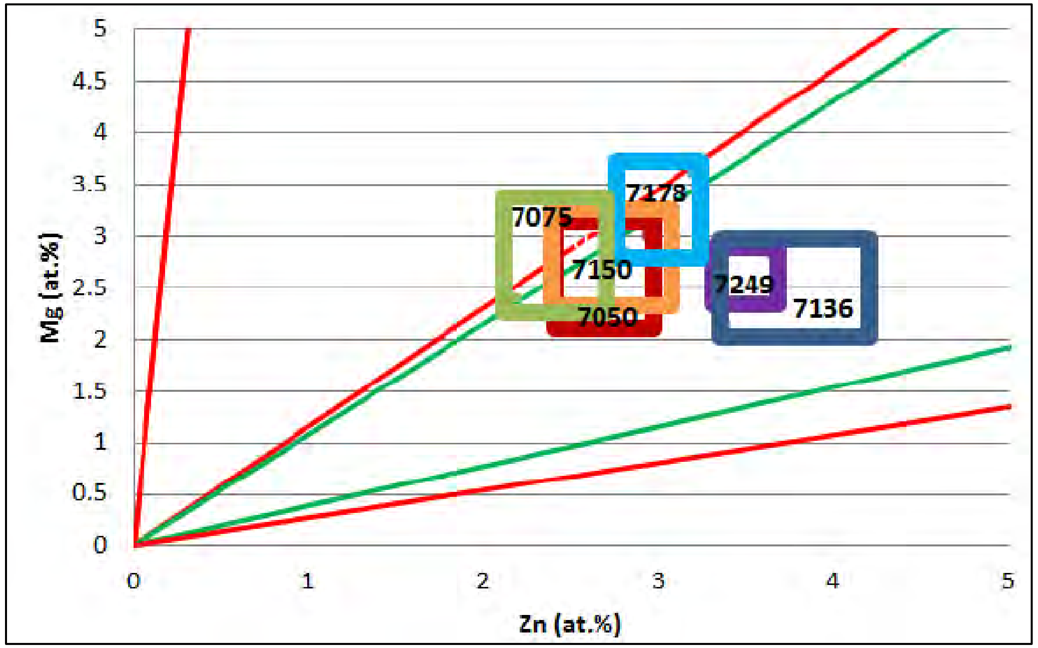
UAC UNIVERSAL ALLOY CORPORATION
A COMPANY OF MONTANA AEROSPACE AG

Introduction

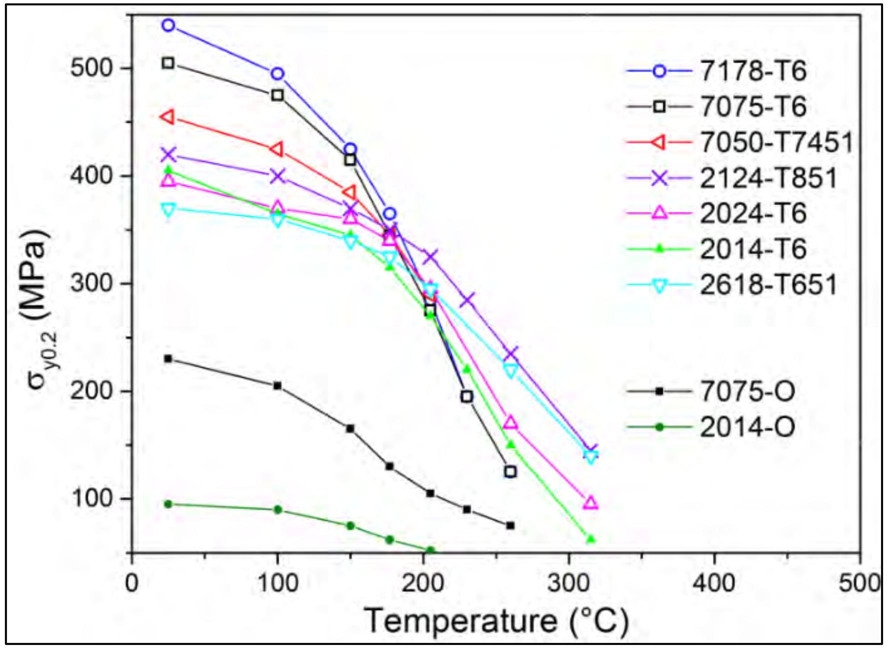
- Universal Alloy Corporation (UAC) has studied HEAC since the EASA SIB bulletins.
  - Focus has been placed on the following:
    1. Understanding the underlying mechanism – published research and internal testing.
    2. Understanding the nuances of the proposed test mechanism in the SIB.
    3. Running tests on various alloy-tempers at different stress levels.

- Hydrogen embrittlement is well known to be an underlying mechanism in classic EAC (SCC, etc.) along with anodic dissolution.
  - Ex. the diffusion of hydrogen to crack tips propagating cracks.
  - HEAC appears to come about from a combination of humidity level, exposure temperature, and stress.
    - The expectation is that like SCC chemical composition, temper, and grain structure also play a role in a component's susceptibility.

HEAC
Critical Questions



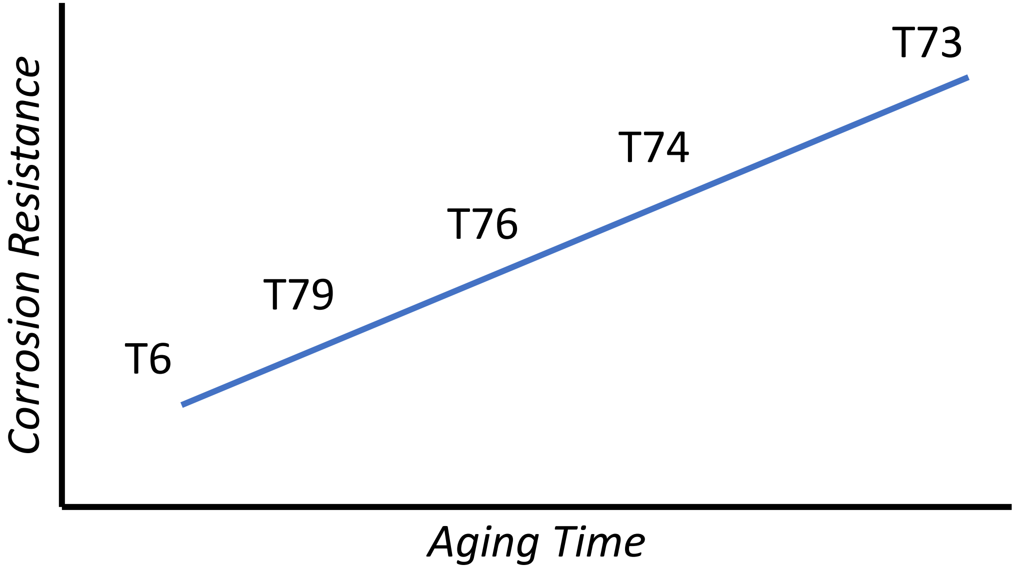
Lamb (2015)

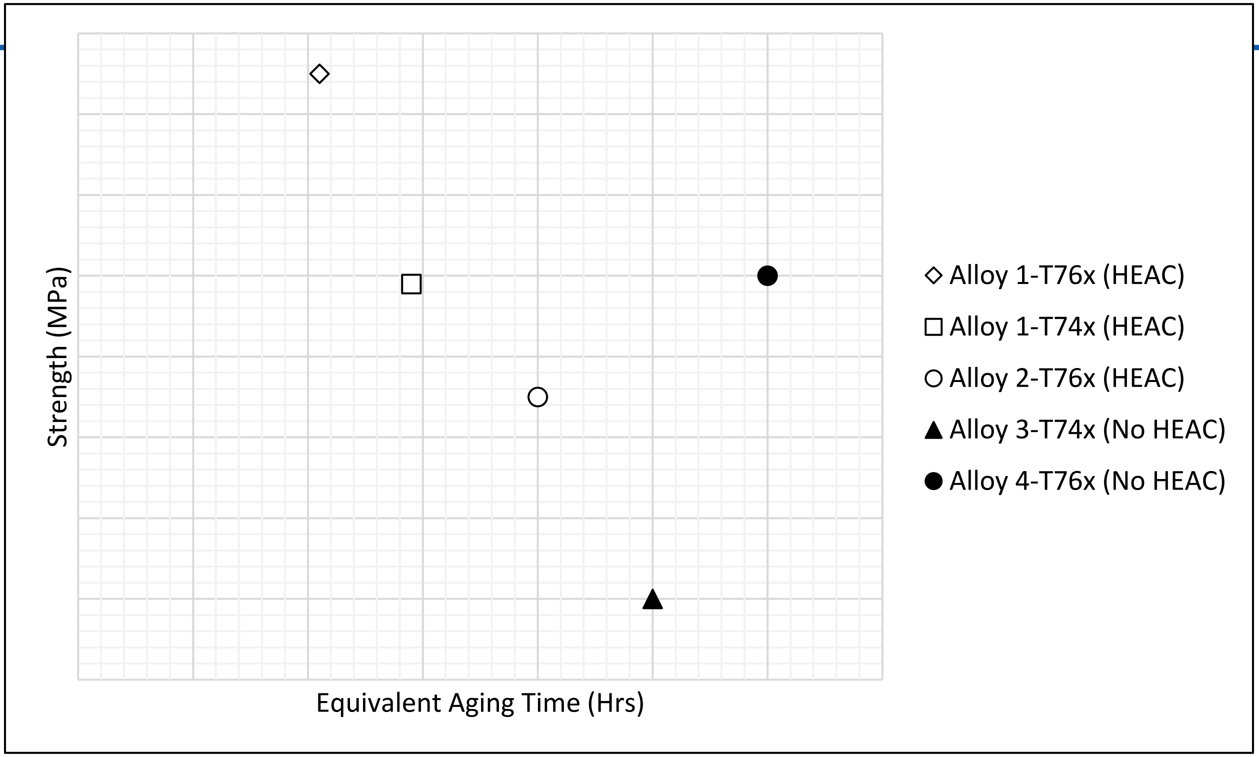


Chobaut (2015)

- What is the role of temperature on HEAC?
  - Aluminum alloys tend to lose strength and experience modulus changes with temperature (ex. MMPDS 7075).
  - Designing for HEAC tends to push one toward T-phase 7xxx-series precipitates instead of η.
    - T-phase is generally avoided in modern alloy design due to issues with SCC and facture toughness.
    - However, T-phase may be better in thermal exposure environments.

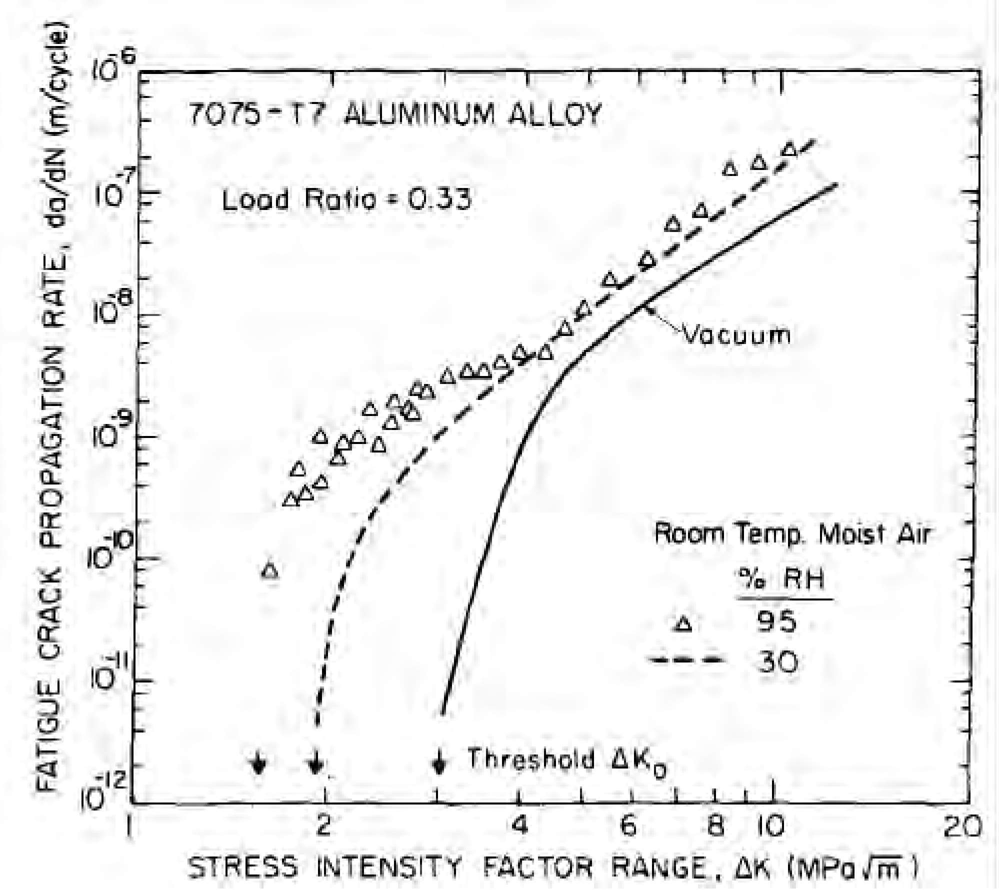
HEAC
Critical Questions (II)





- What is the role of temper on HEAC?
  - The EASA SIB hints that temper may play a crucial role in HEAC resistance (ref. 7040 note).
  - Issue alloys appear to be largely underaged when plotted versus equivalent time.
  - With traditional SCC in 7xxx-series aluminum alloy, corrosion resistance increased with over-aging.

HEAC Testing
EASA SIB and Possible Alternatives



Vasudevan and Suresh (1982)

- The EASA SIB details a "EAC Generic Test Method."
  - The test appears to focus on initiation of EAC.
  - The constant strain test detailed in the EASA SIB has several disadvantages, including duration (recommendation 100 days), a high degree of sensitivity, and the need for advanced characterization techniques (SEM) per test.
- Fatigue Crack Growth Rate (FCGR) tests are known to show sensitivity to the test environment.
  - Crack growth rates in high humidity environments (>90%) are generally faster than in lab air for the same material.
    - Reported mechanisms are similar to those reported for HEAC → could a FCGR test be developed to more easily evaluate materials?

Problem Definition and Knowledge Gaps for 7xxx EAC

J.T. Burns, R.G. Kelly

University of Virginia

Z.D. Harris

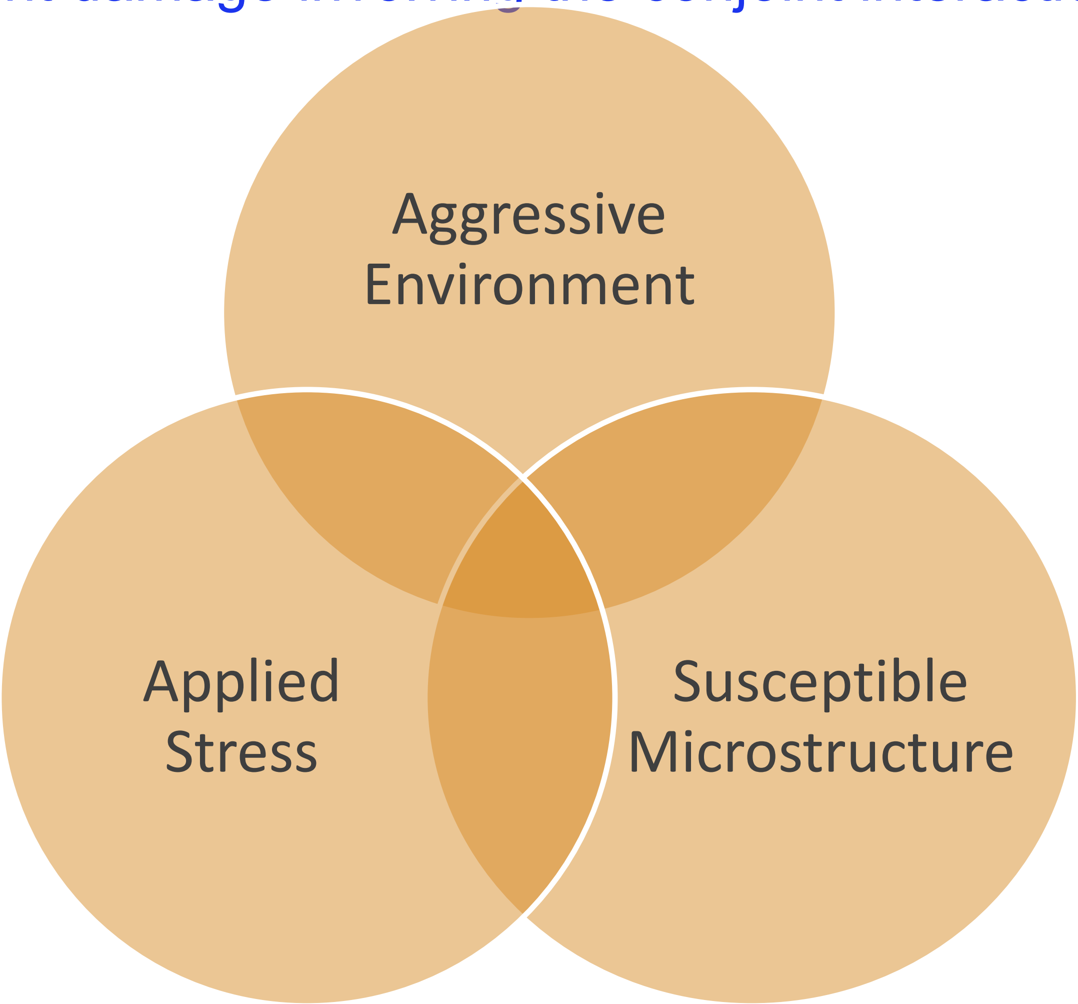
University of Pittsburgh

AFRL-FAA Technical Interchange Meeting (TIM) on Environmentally Assisted Cracking (EAC) / Stress Corrosion Cracking (SCC) of High-Strength 7000 Series Aluminum Alloys

November 2024
Dayton, OH

Damage Mode

Crack formation and stable growth below K_{IC} caused by time-dependent damage involving the conjoint interaction of…..

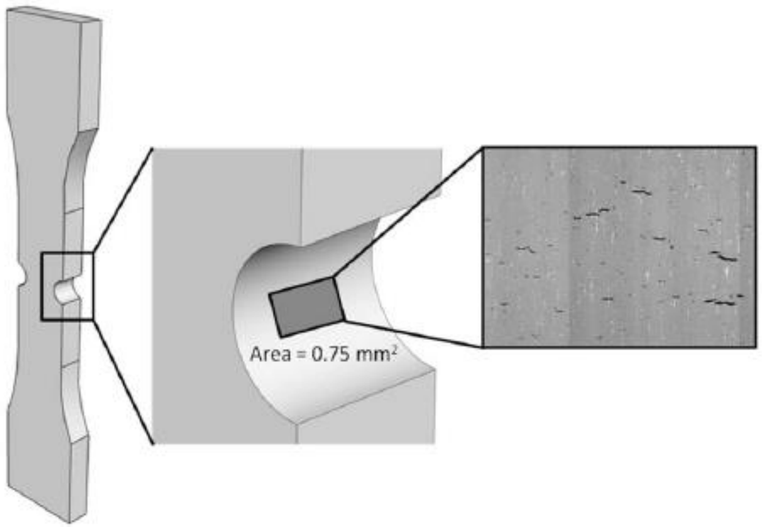


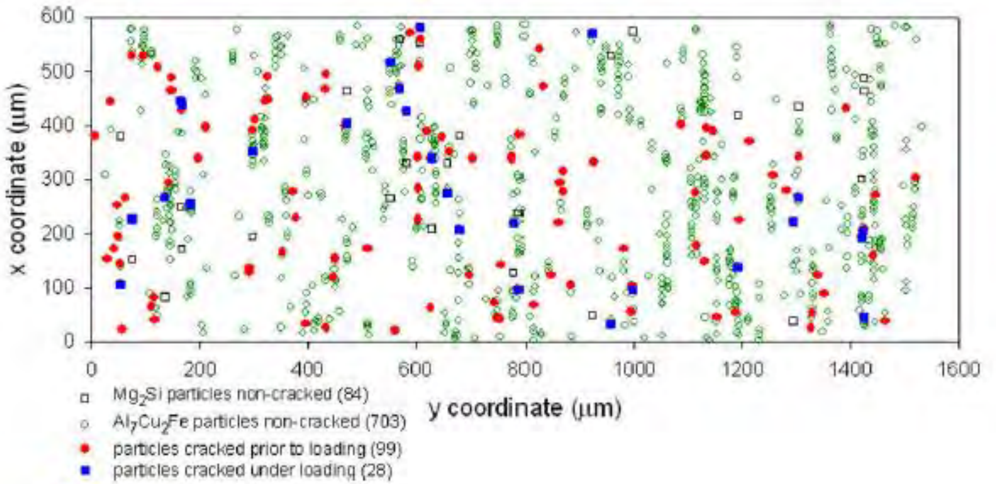
Damage Progression

Step 1: Cracking “pre-cursor”

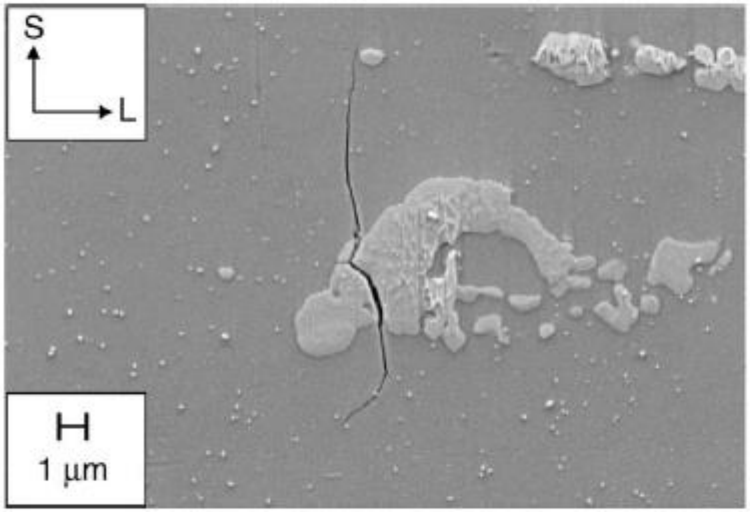
Damage Progression

Step 1: Cracking "pre-cursor"





In the absence of environmental degradation surface defects and/or constituent particles often serve as crack nucleation sites…



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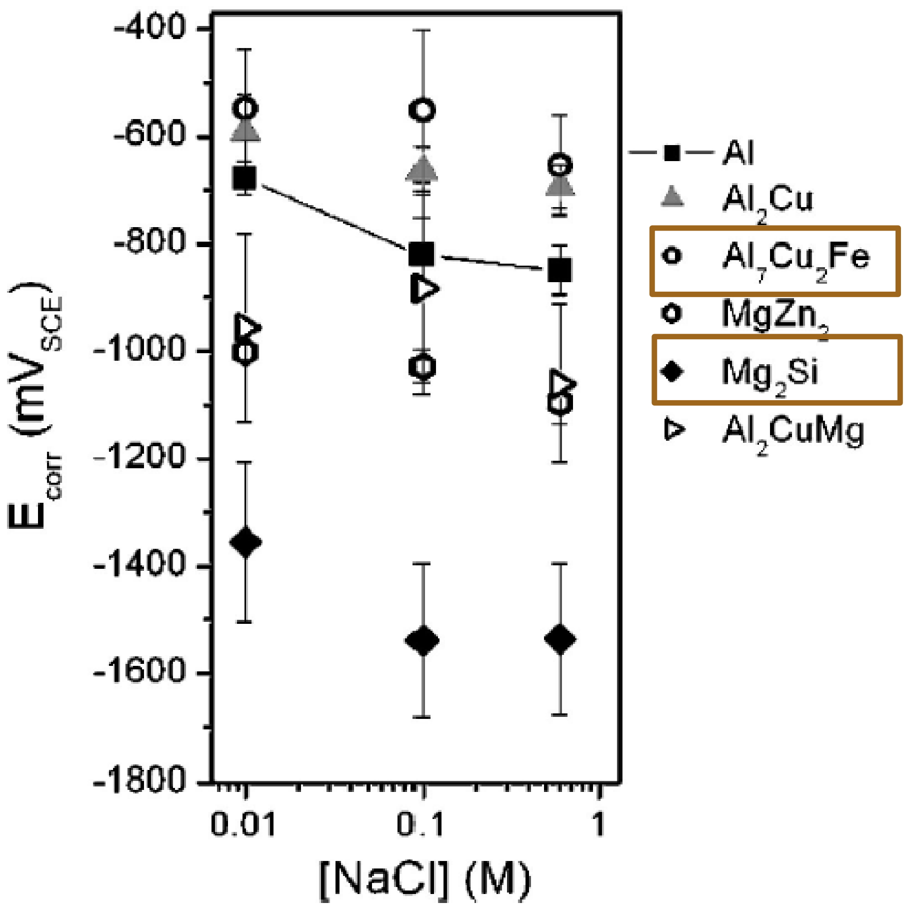
Harlow, Int J Fat, 2010

Damage Progression

Step 1: Cracking "pre-cursor"



These constituent particles are also sites of localized corrosion in the presence of an electrolyte

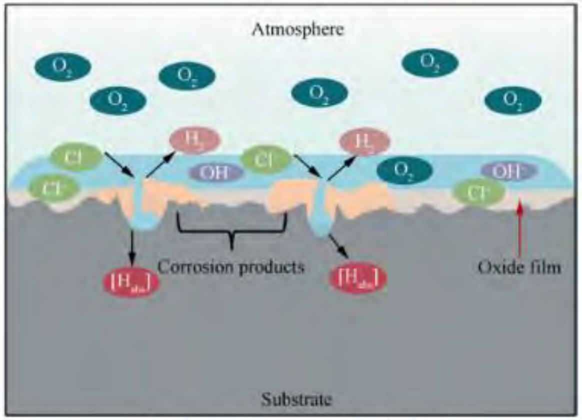
Table III. Pitting potentials for intermetallic compounds common in aluminum alloys. Results are average values incorporating the results of numerous tests.

Stoichiometry	Phase	Pitting potential (mV_{SCE}) 0.01 M	0.1 M	0.6 M	Note
Al_3Fe	β	442	106	−382	
Al_2Cu	θ	−434	−544	−652	
Al_3Zr	β	−223	−275	−346	
Al_6Mn	-	−485	−755	−778	
Al_3Ti	β	−232	−225	−646	
$Al_{32}Zn_{49}$	T′	-	-	-	C
Mg_2Al_3	β	−818	−846	−959	
$MgZn_2$	M, η	-	-	-	C
Mg_2Si	β	-	-	-	C
Al_7Cu_2Fe	-	−447	−448	−580	
Mg (AlCu)	-	224	−2	-	D, E
Al_2CuMg	S	108	80	135	F
$Al_{20}Cu_2Mn_3$	-	−210	−428	−534	
$Al_{12}Mn_3Si$	-	−563	−621	−712	
Al (99.9999)	-	−545	−610	−696	A
Cu (99.9)	-	19	−30	−94	A
Si (99.9995)	α	-	-	-	A, C
Mg (99.9)	-	−1095	−1391	−1473	A, G
Mn (99.9)	-	-	-	-	A, C
Cr (99.0)	-	479	297	190	A
Zn (99.99)	-	-	-	-	A, C
Al-2%Cu	α	−447	−471	−529	B
Al-4%Cu	α	−418	−406	−465	B
7X75 Matrix	-	−633	−736	−768	M
AA 7075-T651	-	−684	−739	−810	X

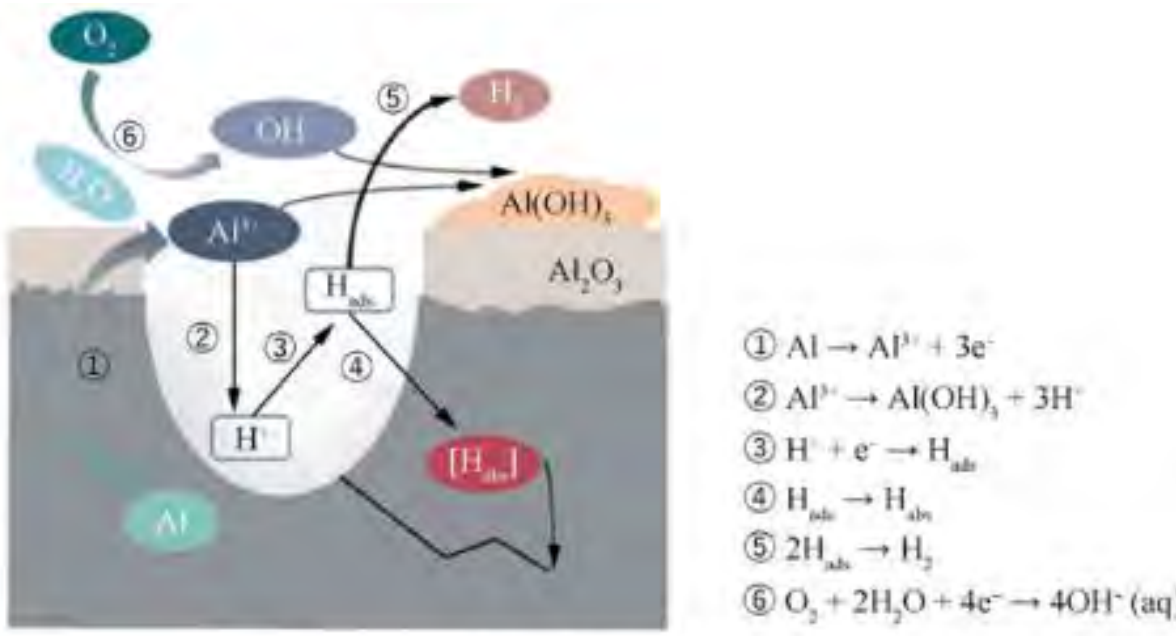
Damage Progression

Step 1: Cracking "pre-cursor"

Localized corrosion leads to local stress concentrators and local H uptake



(b) In TEL environment without $NaHSO_3$



(c) Localized corrosion mechanism in 3.5% NaCl solution environment

Damage Progression

Step 2: Crack Initiation

Damage Progression

Step 2: Crack Initiation

Fundamentally requires the local exceedance of a critical stress/strain value on a microstructural feature

Typically Aided By:

- *Microstructural interface with a low cohesive strength*
- *Local stress/strain concentrators (pit, IG fissure, constituent, HA grain interface, etc)*
- *H-based degradation of the cohesive strength of a microstructural interface*
- *Aggressive local chemistry (due to pit IG, fissure, crevice, etc)*

Damage Progression

Step 2: Crack Initiation

Corrosion damage influences crack formation by…

Aggressive Local Environment

- *Concurrent loading/dissolution*
- *Enhanced aggressive environment within pit*

Enhanced Stress/Strain

- *Global due to decreased cross-sectional area*
- *Local*
  - *Macro- and micro-stress/strain concentrators*
  - *Local microstructure features (constituents, etc.)*

Local Embrittlement

- *H-charging from pre-existing corrosion embrittles material and reduces cohesion*

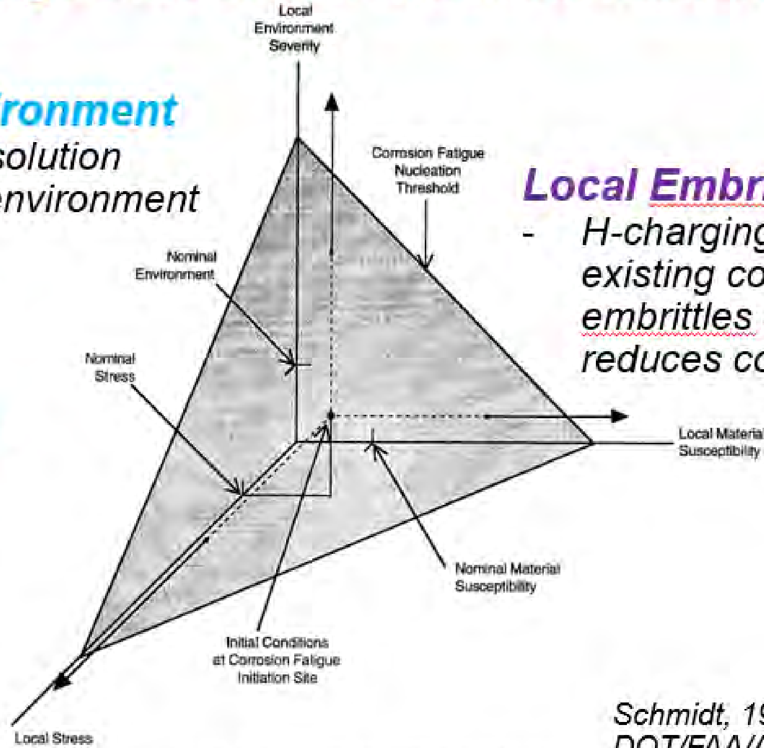


Figure 1. Critical conditions for corrosion-fatigue crack nucleation.

Schmidt, 1996
DOT/FAA/AR-95-108

Damage Progression

Step 2: Crack Initiation

Be aware, but wary of engineering scale (LEFM) models of crack initiation *(e.g. Kondo approach)*

- ***Generally, assume a pit is a crack; when pit size and stress result in K exceeding K_{ISCC}, then initiation…***
- *Issues with (1) violating LEFM crack size assumptions and (2) small cracks through a few grains will not have continuum behavior*
- *Rigorous modeling would required grain scale driving forces and failure criteria (akin to FIPs for fatigue)*

Damage Progression

Step 3: Small Crack Growth

Both:

- **Chemically small**

- **Mechanically small**
  - *Where cracking through a few grains*

	SHORT CRACK	MICROSTRUCTURAL SMALL CRACK
	• $r_{pc} >> gs$ • Many grains @ front	• in 1 to 5 grains
MECHANICAL	SMALL SCALE YIELDING NOT MAINTAINED • High σ_{NET} • $a < 1$ to $5\ r_p$	ENHANCED CRACK TIP STRAIN • $a < gs$ • $r_{pc} < 1$ to $2\ gs$
PHYSICAL	REDUCED CRACK WAKE CLOSURE • $a < 1$ mm	
CHEMICAL	CRACK SIZE DEPENDENT OCCLUDED CHEMISTRY • $a < 5$ to 10 mm	

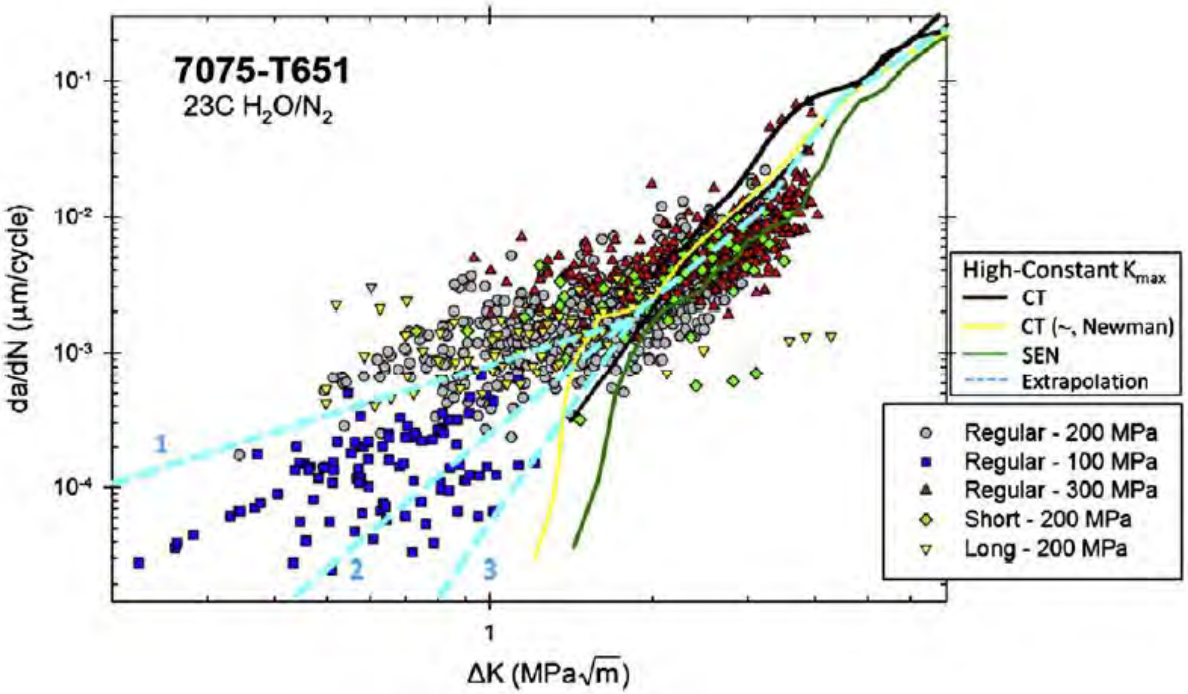
r_p – monotonic plastic zone   a – crack length
r_{pc} – cyclic plastic zone   gs – grain size

Damage Progression

Step 3: Small Crack Growth

Both:

- **Chemically small**
- **Mechanically small**
  - *Where cracking through a few grains*
  - ***Results in a lot of variability and difficult to characterize***



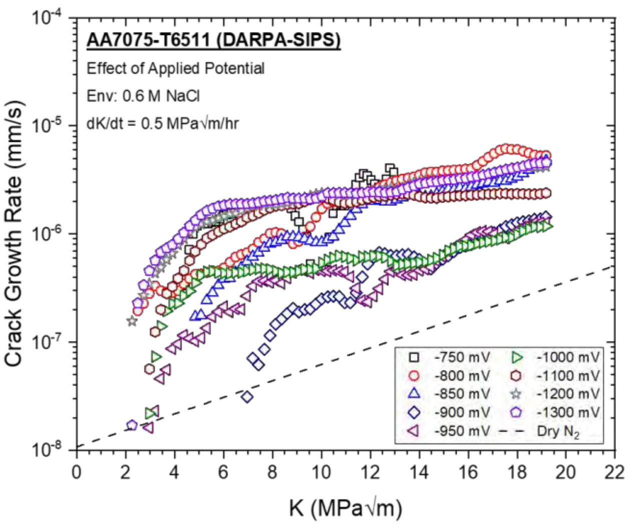
Damage Progression

Step 4: Continuum scale crack growth

- ***Crack is interacting with a large number of grains and you get continuum scale behavior (LEFM will work)***
  - *da/dt = f(K); K = σ √πa (β)*

- ***Well established techniques for generating da/dt vs K data (ISO standard available, improved ASTM standard underway)***
  - *Able to pull out continuum scale threshold and Stage II kinetics*

- ***Can generate data for relevant/bounding environments; important to ensure environmental similitude***

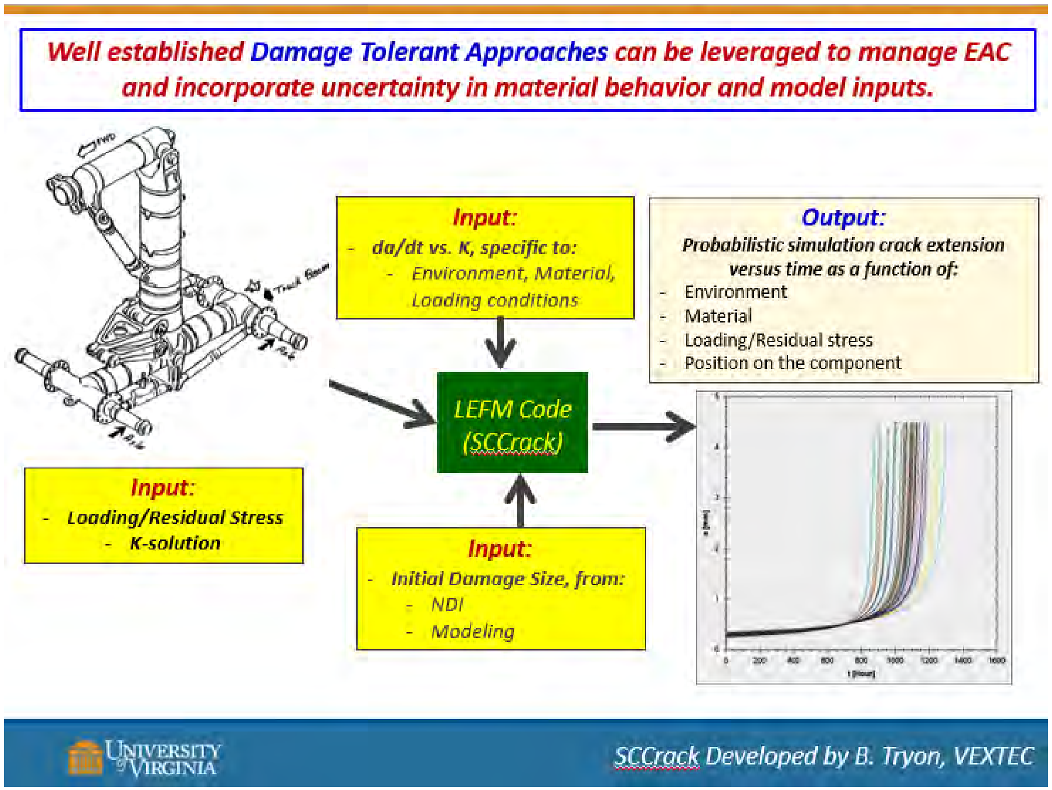


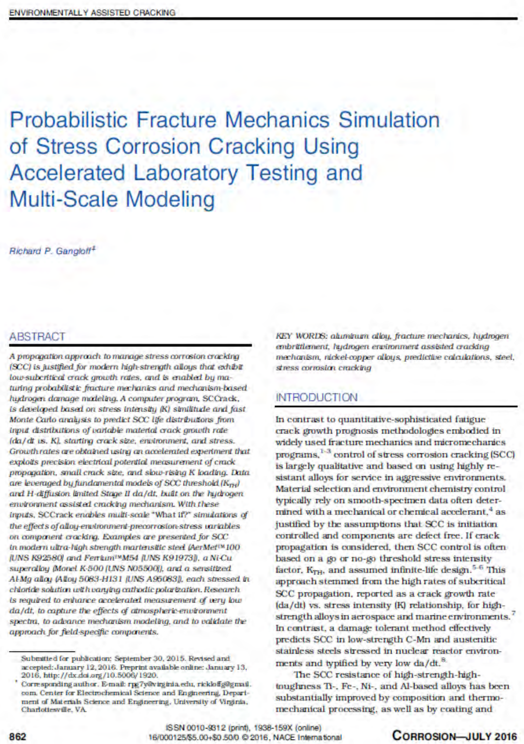
University of Virginia

Damage Progression

Step 4: Continuum scale crack growth

- ***Commercial software exists to enable LEFM-based EAC life prediction***
  - *Akin to AFGROW, NASGROW, BEASY for fatigue*
  - *Simplistically, integration of da/dt = f(K); can add probablistics*





ENVIRONMENTALLY ASSISTED CRACKING

Probabilistic Fracture Mechanics Simulation of Stress Corrosion Cracking Using Accelerated Laboratory Testing and Multi-Scale Modeling

Richard P. Gangloff[‡]

ABSTRACT

A propagation approach to manage stress corrosion cracking (SCC) is justified for modern high-strength alloys that exhibit low-subcritical crack growth rates, and is enabled by maturing probabilistic fracture mechanics and mechanism-based hydrogen damage modeling. A computer program, SCCrack, is developed based on stress intensity (K) similitude and fast Monte Carlo analysis to predict SCC life distributions from input distributions of variable material crack growth rate (da/dt vs. K), starting crack size, environment, and stress. Growth rates are obtained using an accelerated experiment that exploits precision electrical potential measurement of crack propagation, small crack size, and slow-rising K loading. Data are leveraged by fundamental models of SCC threshold (K_{TH}) and H-diffusion limited Stage II da/dt, built on the hydrogen environment assisted cracking mechanism. With these inputs, SCCrack enables multi-scale "What If?" simulations of the effects of alloy-environment-precorrosion-stress variables on component cracking. Examples are presented for SCC in modern ultra-high strength martensitic steel (AerMet™100 [UNS K92580] and Ferrium™M54 [UNS K91973]), a Ni-Cu superalloy (Monel K-500 [UNS N05500]), and a sensitized Al-Mg alloy (Alloy 5083-H131 [UNS A95083]), each stressed in chloride solution with varying cathodic polarization. Research is required to enhance accelerated measurement of very low da/dt, to capture the effects of atmospheric-environment spectra, to advance mechanism modeling, and to validate the approach for field-specific components.

KEY WORDS: aluminum alloy, fracture mechanics, hydrogen embrittlement, hydrogen environment assisted cracking mechanism, nickel-copper alloys, predictive calculations, steel, stress corrosion cracking

INTRODUCTION

In contrast to quantitative-sophisticated fatigue crack growth prognosis methodologies embodied in widely used fracture mechanics and micromechanics programs,[1-3] control of stress corrosion cracking (SCC) is largely qualitative and based on using highly resistant alloys for service in aggressive environments. Material selection and environment chemistry control typically rely on smooth-specimen data often determined with a mechanical or chemical accelerant,[4] as justified by the assumptions that SCC is initiation controlled and components are defect free. If crack propagation is considered, then SCC control is often based on a go or no-go threshold stress intensity factor, K_{TH}, and assumed infinite-life design.[5-6] This approach stemmed from the high rates of subcritical SCC propagation, reported as a crack growth rate (da/dt) vs. stress intensity (K) relationship, for high-strength alloys in aerospace and marine environments.[7] In contrast, a damage tolerant method effectively predicts SCC in low-strength C-Mn and austenitic stainless steels stressed in nuclear reactor environments and typified by very low da/dt.[8]

The SCC resistance of high-strength-high-toughness Ti-, Fe-, Ni-, and Al-based alloys has been substantially improved by composition and thermo-mechanical processing, as well as by coating and

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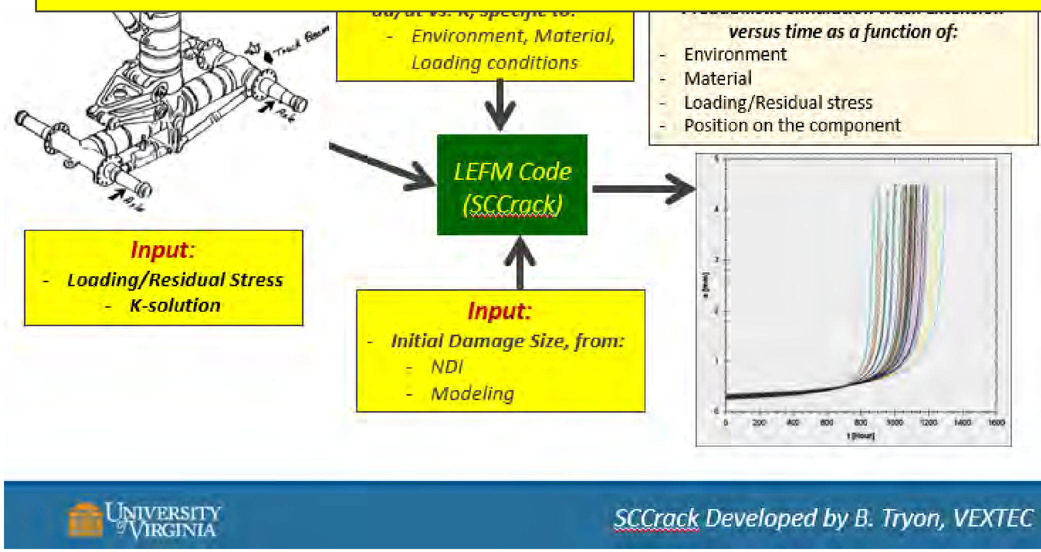
Damage Progression

Step 4: Continuum scale crack growth

- ***Commercial software exists to enable LEFM-based EAC life prediction***
  - *Akin to AFGROW, NASGROW, BEASY for fatigue*
  - *Simplistically, integration of da/dt = f(K); can add probablistics*

Can be very accurate, but predictions will only be as good as the material/environment property (da/dt vs K) and accuracy of stress input



Richard P. Gangloff‡

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Damage Progression

Step 5: Crack growth until exceedance of a_{crit} (e.g. failure)

Damage Progression

Total Life =

Time for Step 1: Precursor development

\+ Time for Step 2: Crack initiation

\+ Time for Step 3: Small crack growth

\+ Time for Step 4: Long crack growth

Damage Progression

Total Life =

Time for Step 1: Precursor development

+ Time for Step 2: Crack initiation

+ Time for Step 3: Small crack growth

+ Time for Step 4: Long crack growth

It is important to remember this when considering testing approaches….

Damage Mechanism

Damage Mechanism

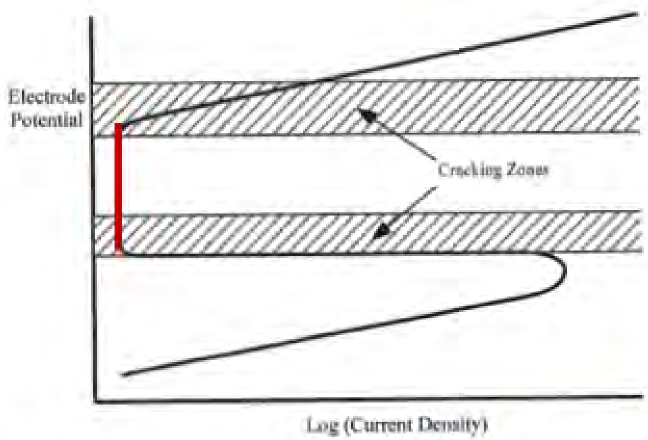
Prominent SCC/EAC Mechanisms are:

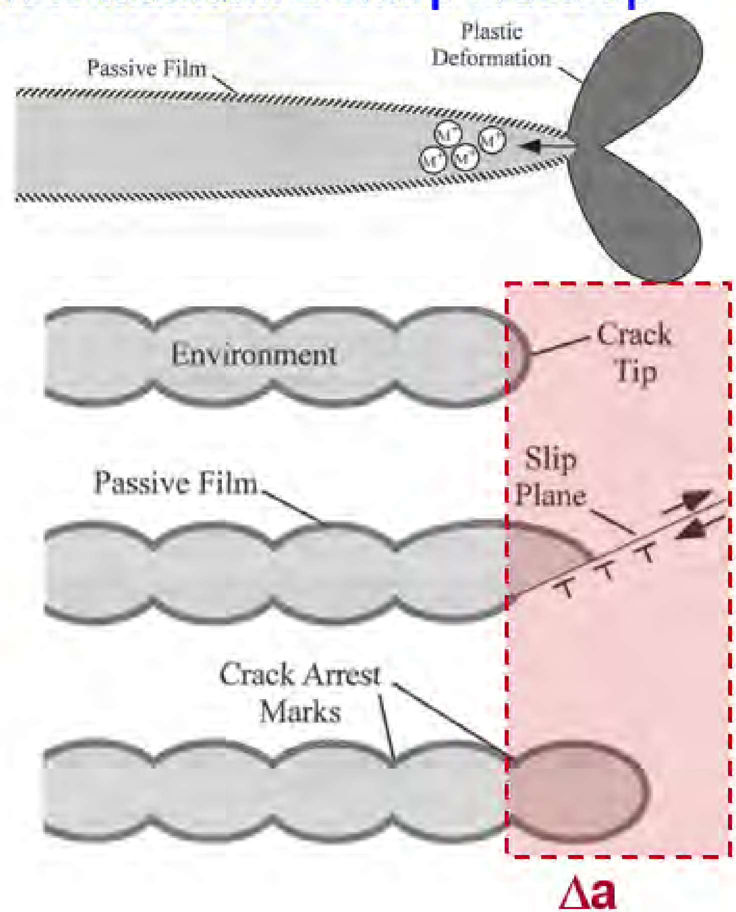
- **Stress-assisted anodic dissolution**
- **Film Rupture-based**
- **Hydrogen Embrittlement**

Damage Mechanism

Mechanism *Crack Tip Passivation + Film Rupture*

EAC SCC can occur in metal-environment systems where crack wall passivation limits metal dissolution to maintain a sharp crack tip





Crack tip plastic strain breaks passive oxide, then local metal dissolution and repassivation occur for crack growth, Δa

Process repeats

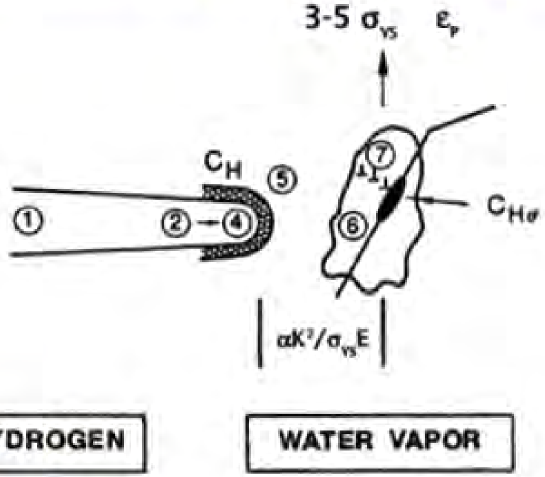
1. Anderson, 2005

Damage Mechanism

Mechanism — Hydrogen Environment Assisted Cracking

Many gaseous and aqueous environments react with Fe, Ni, Al, Ti alloys to produce atomic hydrogen ($H_{adsorbed}$) on the crack tip surface

Atomic H embrittles most metals by several mechanisms discussed in the next lecture



$H \rightarrow 2H_{adsorbed}$

$H_2O + M \rightarrow M_XO_Y + H_{adsorbed}$

$M^{+X} + H_2O \rightarrow M_X(OH)_Y + H^+$

$H^+ + e^- \rightarrow H_{adsorbed}$

5. Gangloff, 2003

Damage Mechanism

Mechanism **Hydrogen Environment Assisted Cracking**

Substantial literature supporting an important role of H-embrittlement 7xxx-series EAC

Thompson AW, Mueller MP, Bernstein IM. Stress-corrosion cracking in equiaxed 7075 aluminum under tension and torsion loading. Metall Trans A 1993;24:2569–75.

Gruhl W. Stress corrosion cracking of high strength aluminum alloys. Zeitschrift Fur Met 1984;75:819–26.

Cooper KR, Young LM, Gangloff RP, Kelly RG. Electrode potential dependence of environment-assisted cracking of AA 7050. Mater Sci Forum 2000;331–337:1625–34.

Young GA, Scully JR. The effects of test temperature, temper, and alloyed copper on the hydrogen-controlled crack growth rate of an Al-Zn-Mg-(Cu) alloy (Metallurgical And Materials Transactions A (January 2002) 33A (101-115)). Metall Mater Trans A Phys Metall Mater Sci 2002;33:1167–81.

See Burns/Harris 7xxx EAC review for all 663 references ☺

5. Gangloff, 2003

$$M^{+X} + H_2O \rightarrow M_X(OH)_Y + H^+$$
$$H^+ + e^- \rightarrow H_{adsorbed}$$

33

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Damage Mechanism

Where does H come from??

to form H_2 gas. During Al oxidation in humid air the following reaction sequence occurs spontaneously or naturally. First aluminum is oxidized in water vapor to form oxide according to the following half cell reaction:

$$2Al + 3H_2O \rightarrow Al_2O_3 + 6H^+ + 6e^- \qquad [19.2]$$

In acid water, the following half cell reaction must occur 6 times in order to support Al oxidation to Al(III) as indicated in Equation 19.2:

$$H^+ + e^- \rightarrow H_{ads}(c) \qquad [19.3]$$

In neutral waters, the following reaction occurs instead of Eq. 19.3:

$$H_2O + e^- \rightarrow H_{ads}(c) + OH^- \qquad [19.4]$$

Damage Mechanism

Where does H come from??

Atomic H Can Be Generated in:

- *Humid air environment*
- *Electrolyte via cathodic polarization*
- *Electrolyte via anodic polarization*

The amount of H formed is dependent on the water content, temperature, electrolyte composition, and polarization level

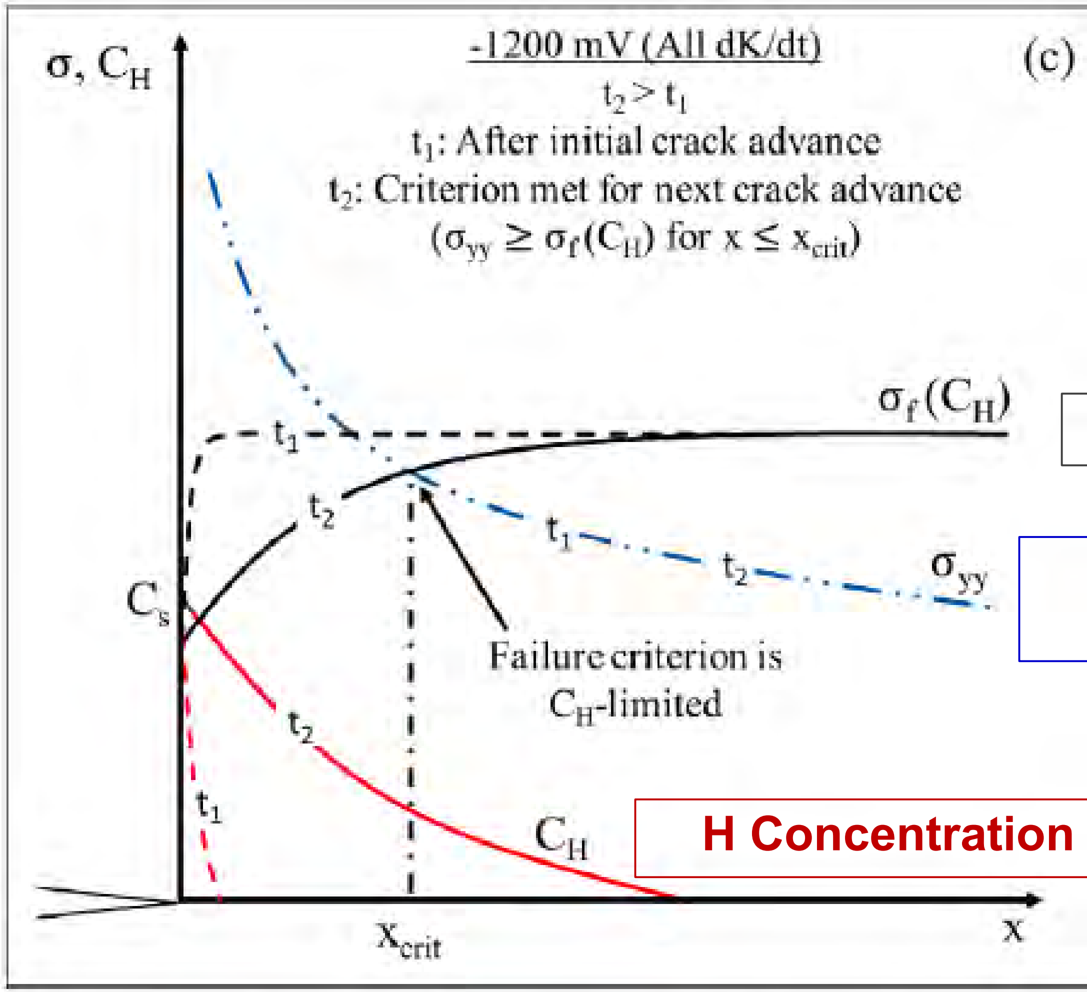
In neutral waters, the following reaction occurs instead of Eq. 19.3:

$$H_2O + e^- \rightarrow H_{ads}(c) + OH^- \qquad [19.4]$$

Damage Mechanism

Ritchie-Knott-Rice (RKR)-type damage model can be used to understand the initiation, small crack growth and continuum scale growth

Damage Mechanism



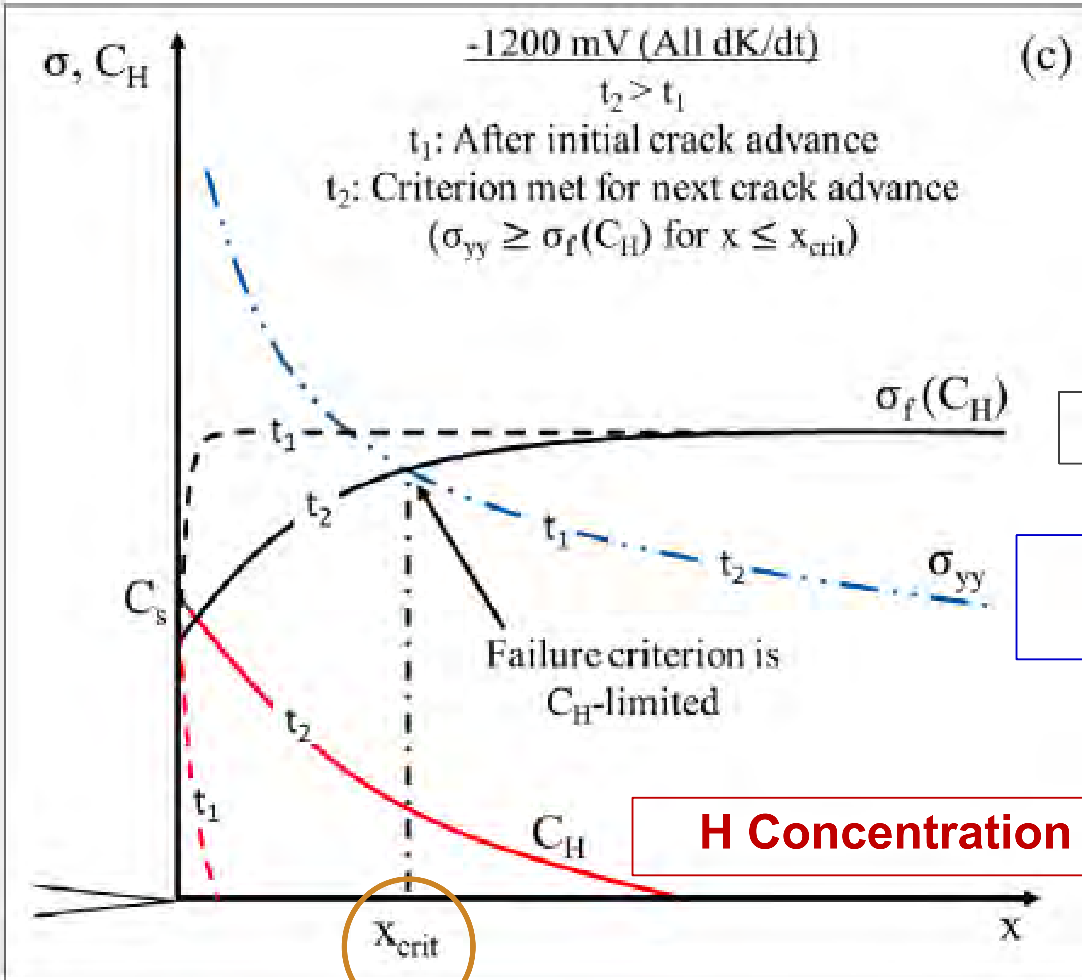
Ritchie-Knott-Rice (RKR)-type damage model

Material Resistance

Opening stress

H Concentration

Damage Mechanism



Material Resistance

Opening stress

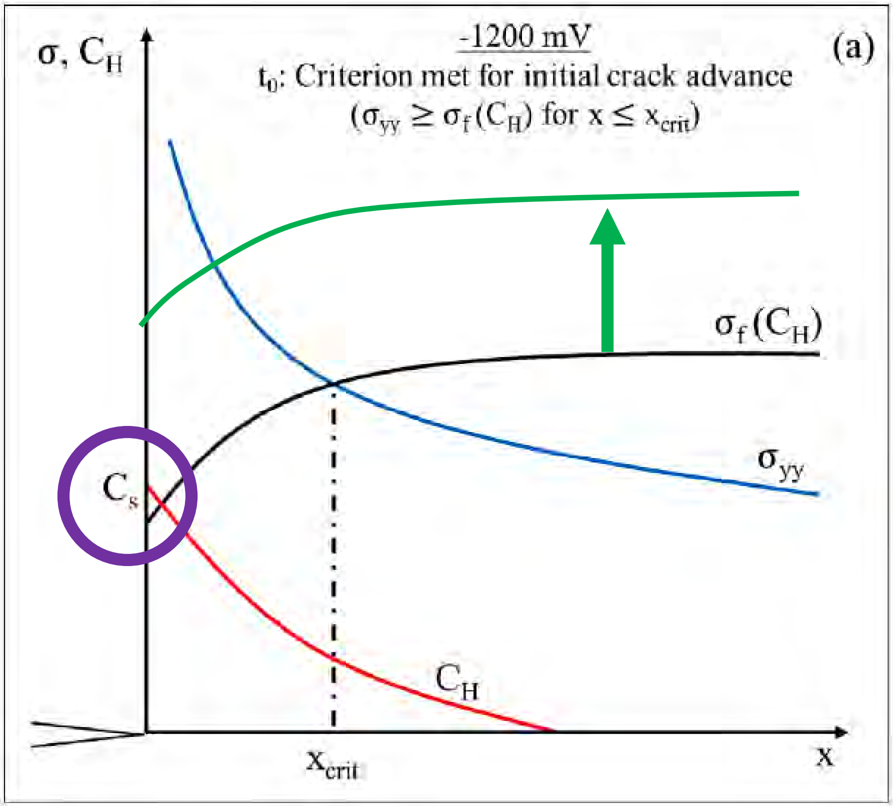
H Concentration

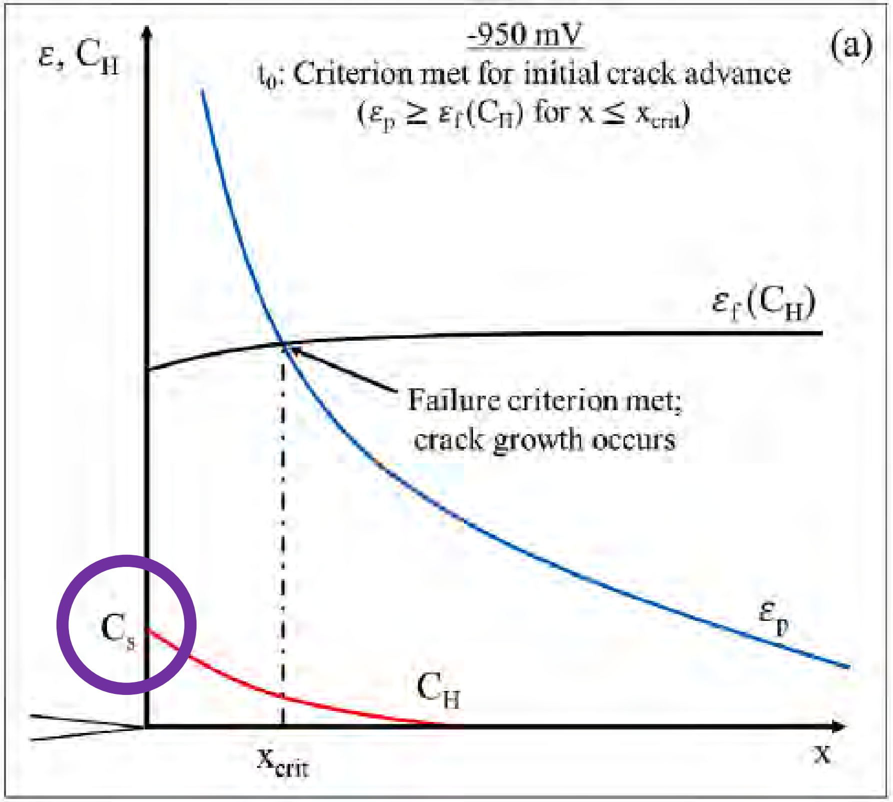
Ritchie-Knott-Rice (RKR)-type damage model

Opening stress must exceed material resistance over X_{crit} for crack initiation or advance

Damage Mechanism

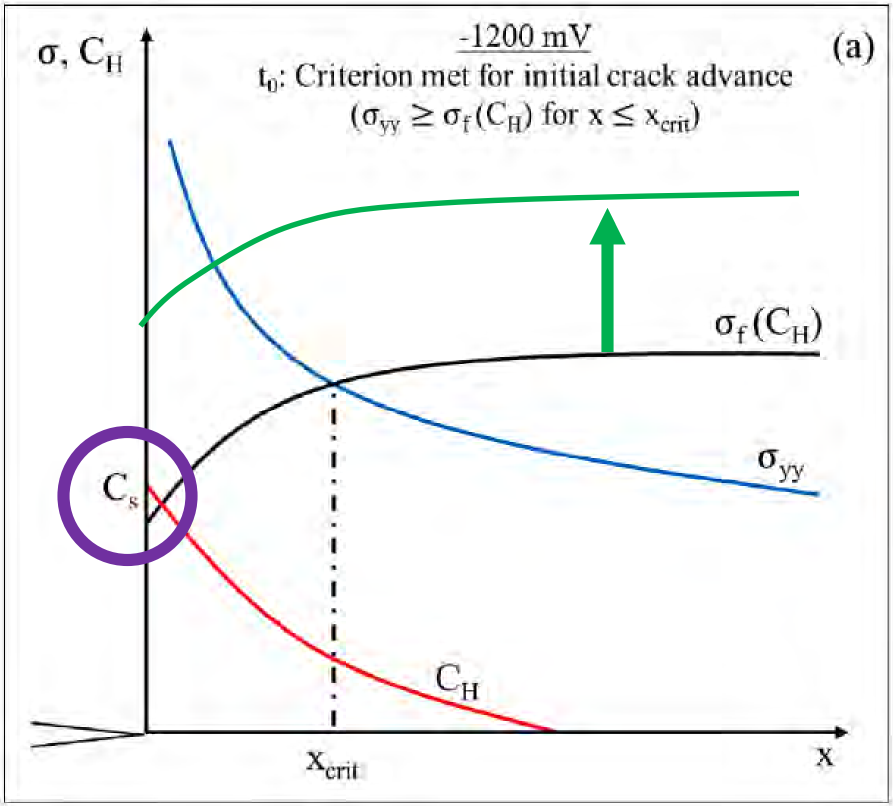
Can move to a "Strain Controlled" Failure if ENVIRONMENT is less severe or the MATERIAL is more resistant…

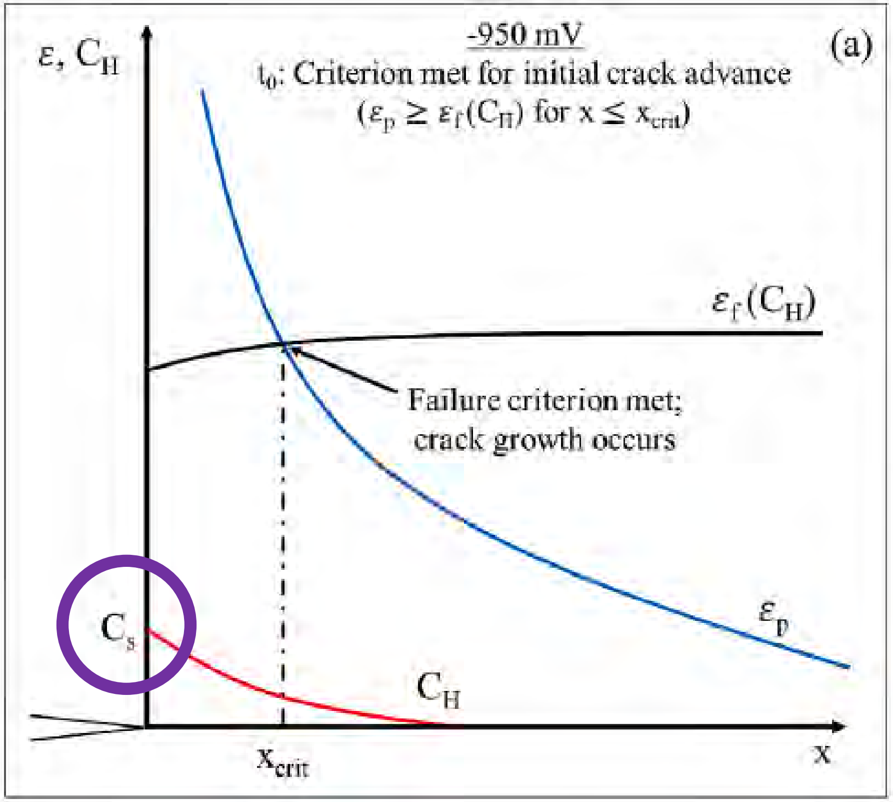




Damage Mechanism

Can move to a "Strain Controlled" Failure if ENVIRONMENT is less severe or the MATERIAL is more resistant…





Strain-control results in loading rate dependence…

Material/Environmental Sensitivities

Well-known phenomenological sensitivities can be rationalized in this paradigm

Sensitivities of 7xxx EAC:

- *Aging*
- *Composition*
- *GB PPCs and segregation*
- *Re-crystallization*
- *Plate thickness*
- *Polarization dependence*
- *Bulk electrolyte chemistry dependence*
- *Water content*
- *Temperature*

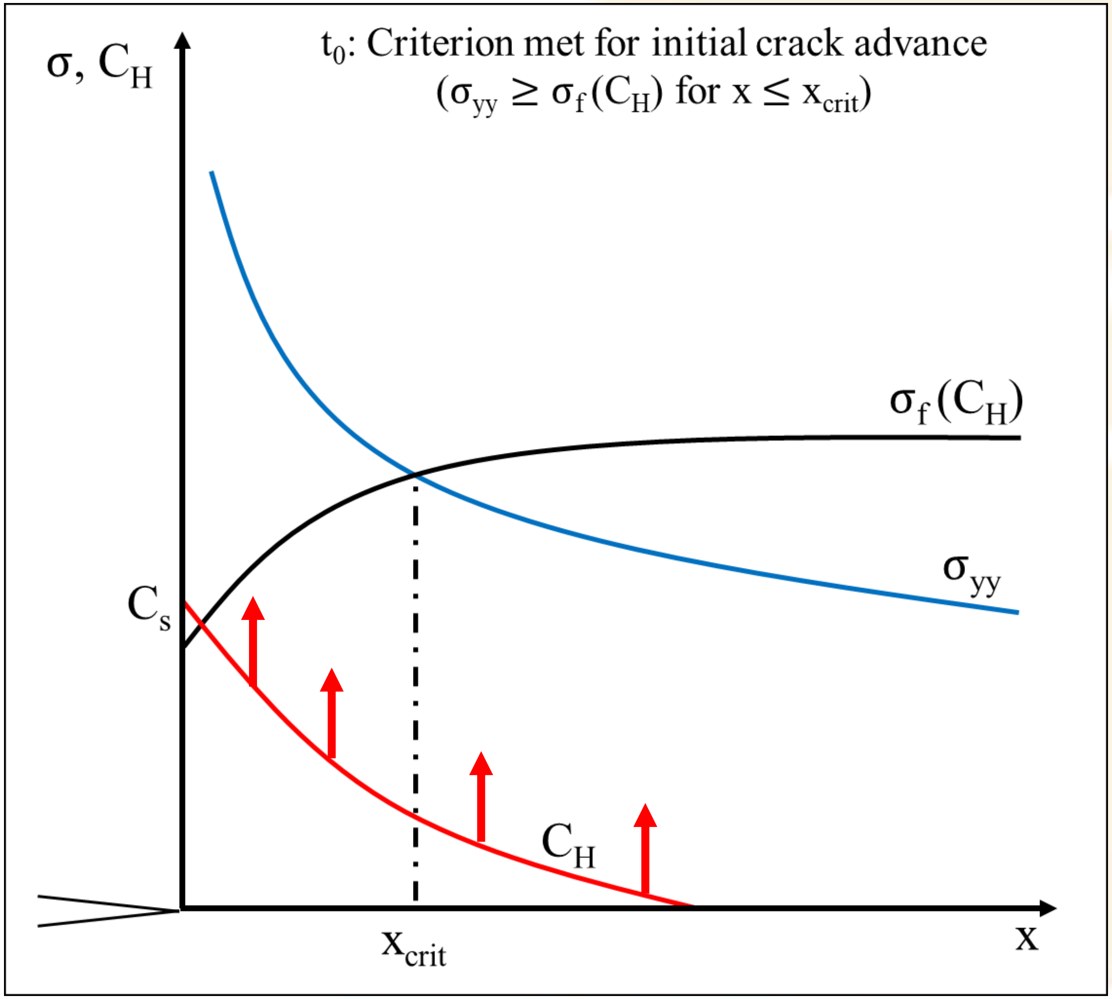
Material/Environmental Sensitivities

Well-known phenomenological sensitivities can be rationalized in this paradigm

1. Modify C_H

Material

- *GB composition (changes the crack tip chemistry)*
- *H-uptake behavior*
- *Oxide stability*
- *Re-passivation behavior*
- *Diffusivity*



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Well-known phenomenological sensitivities can be rationalized in this paradigm

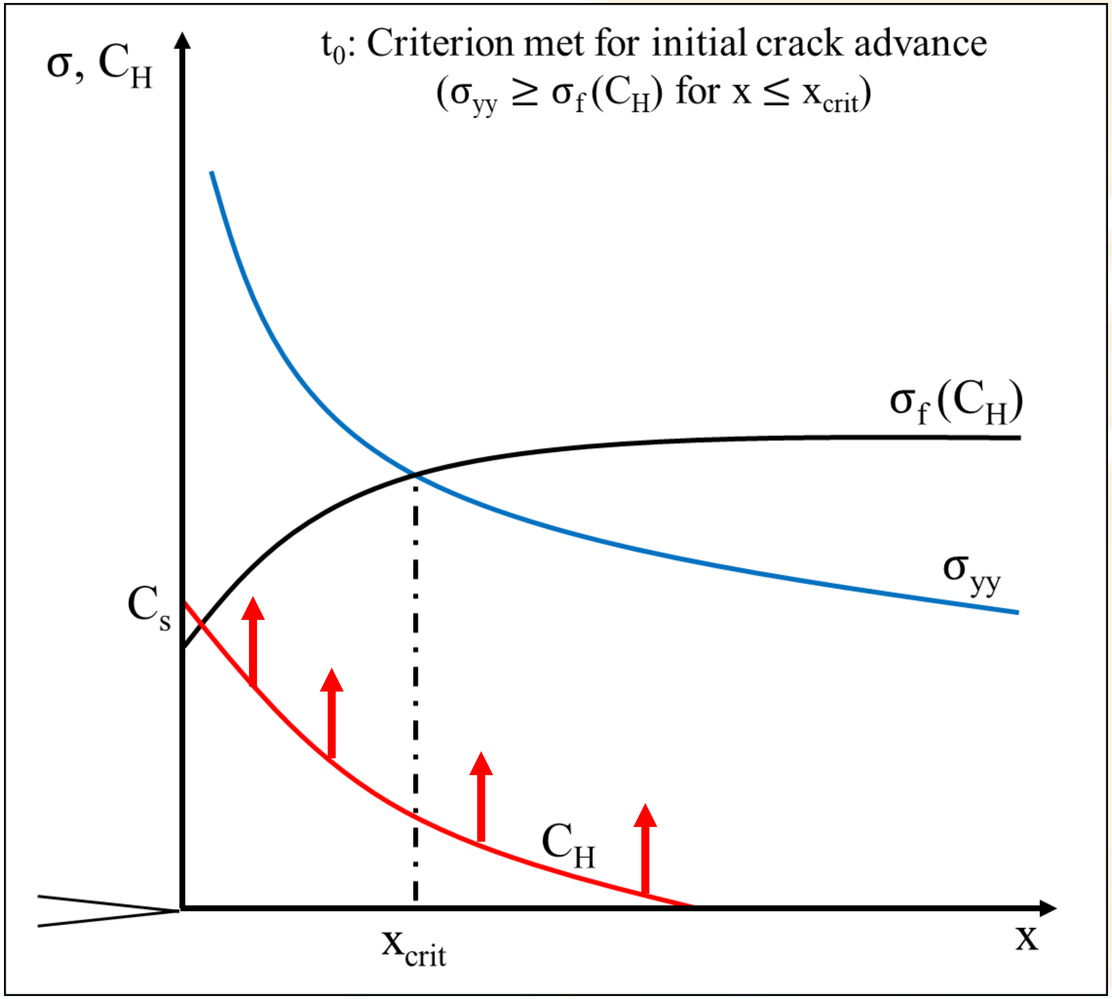
1. Modify C_H

Material

- *GB composition (changes the crack tip chemistry)*
- *H-uptake behavior*
- *Oxide stability*
- *Re-passivation behavior*
- *Diffusivity*

Environment

- *Polarization*
- *Electrolyte composition*
- *Humid air water content*
- *Temperature*



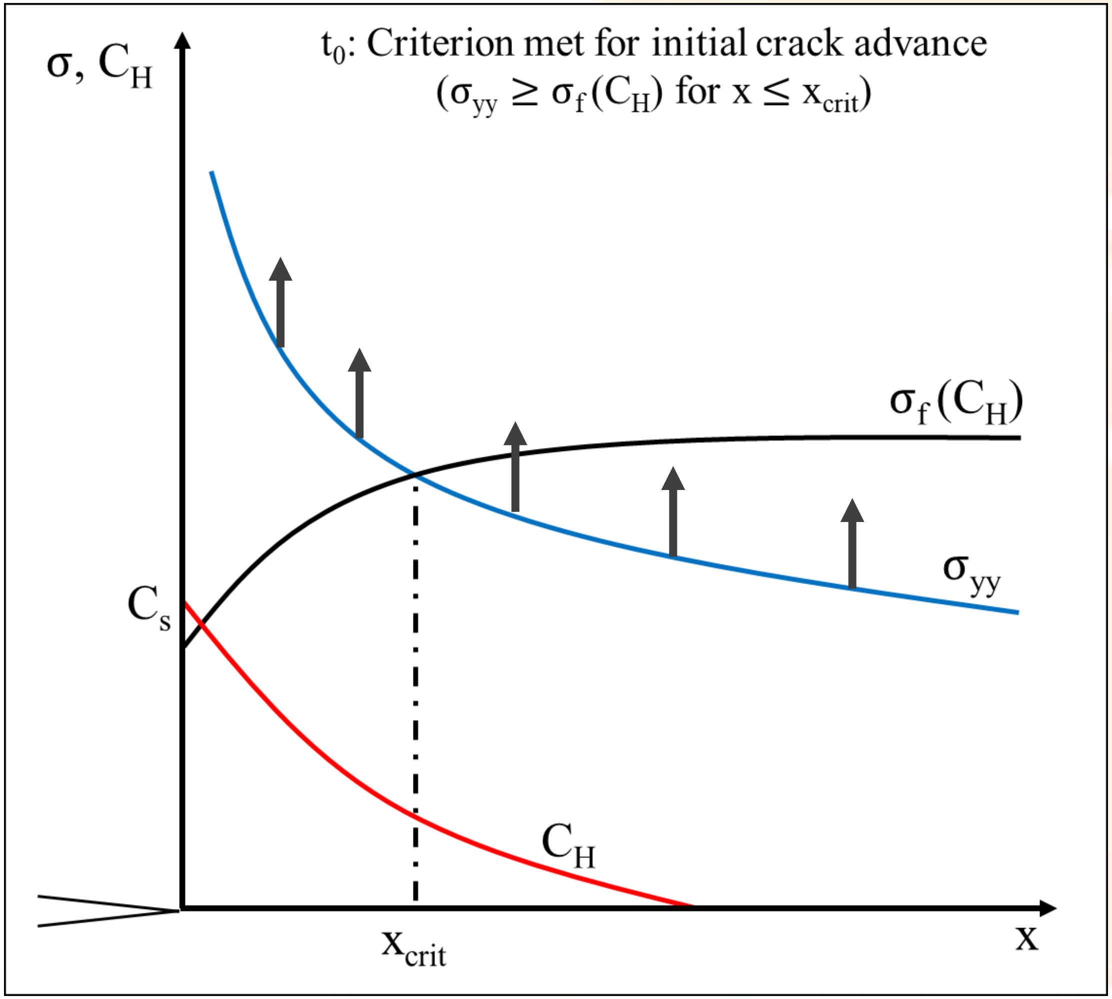
Material/Environmental Sensitivities

Well-known phenomenological sensitivities can be rationalized in this paradigm

2. Modify σ_{yy}

Material
- *Aging/Plate thickness*
  - *Slip planarity*
  - *Hardening behavior*
- *Tortuous crack path (lower macro-scale K)*
- *GB PPCs*
- *PFZ*

Environment
- *Temperature*



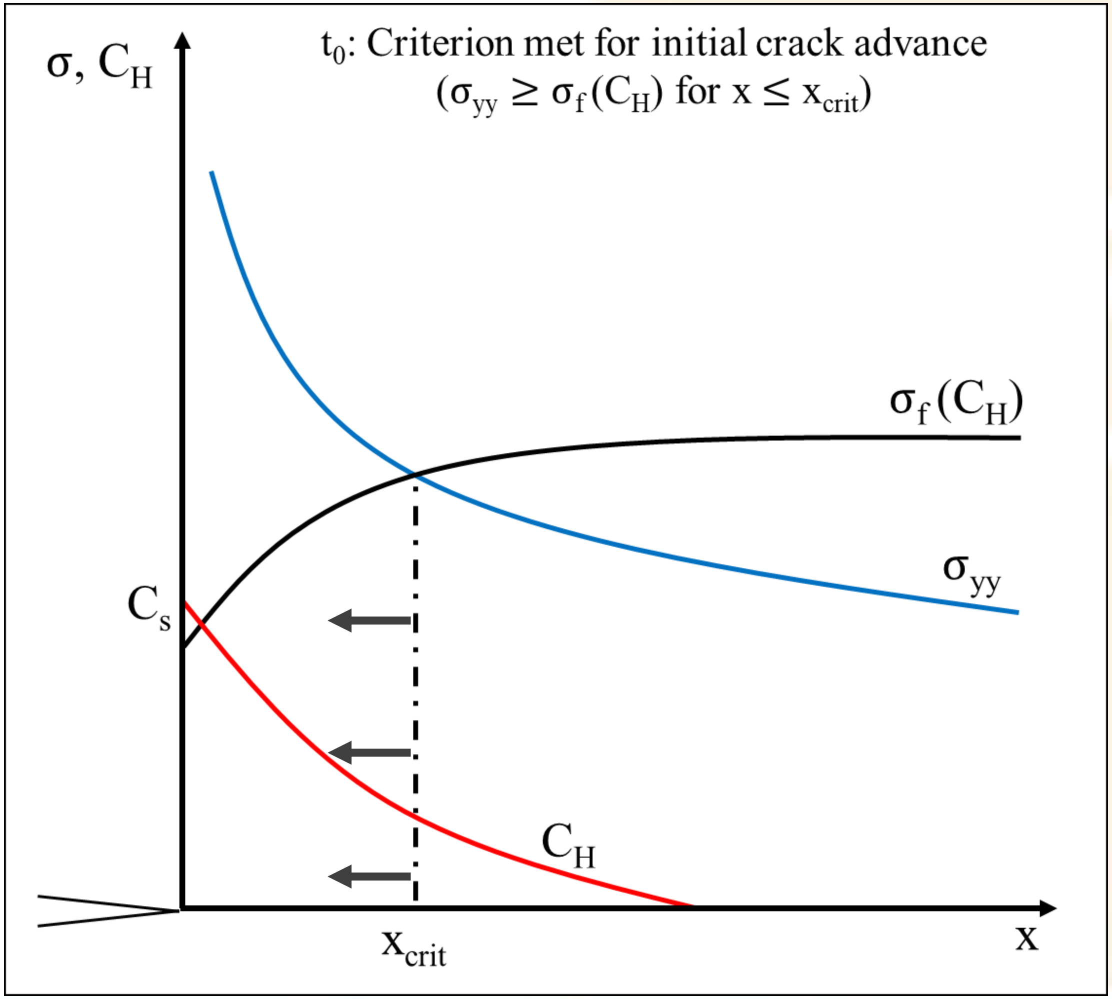
Material/Environmental Sensitivities

Well-known phenomenological sensitivities can be rationalized in this paradigm

3. Modify x_{crit}

Material
- *Change of grain size*
- *Recrystallization structure*
- *PPC spacing*

Environment
- *N/A*



Material/Environmental Sensitivities

Well-known phenomenological sensitivities can be rationalized in this paradigm

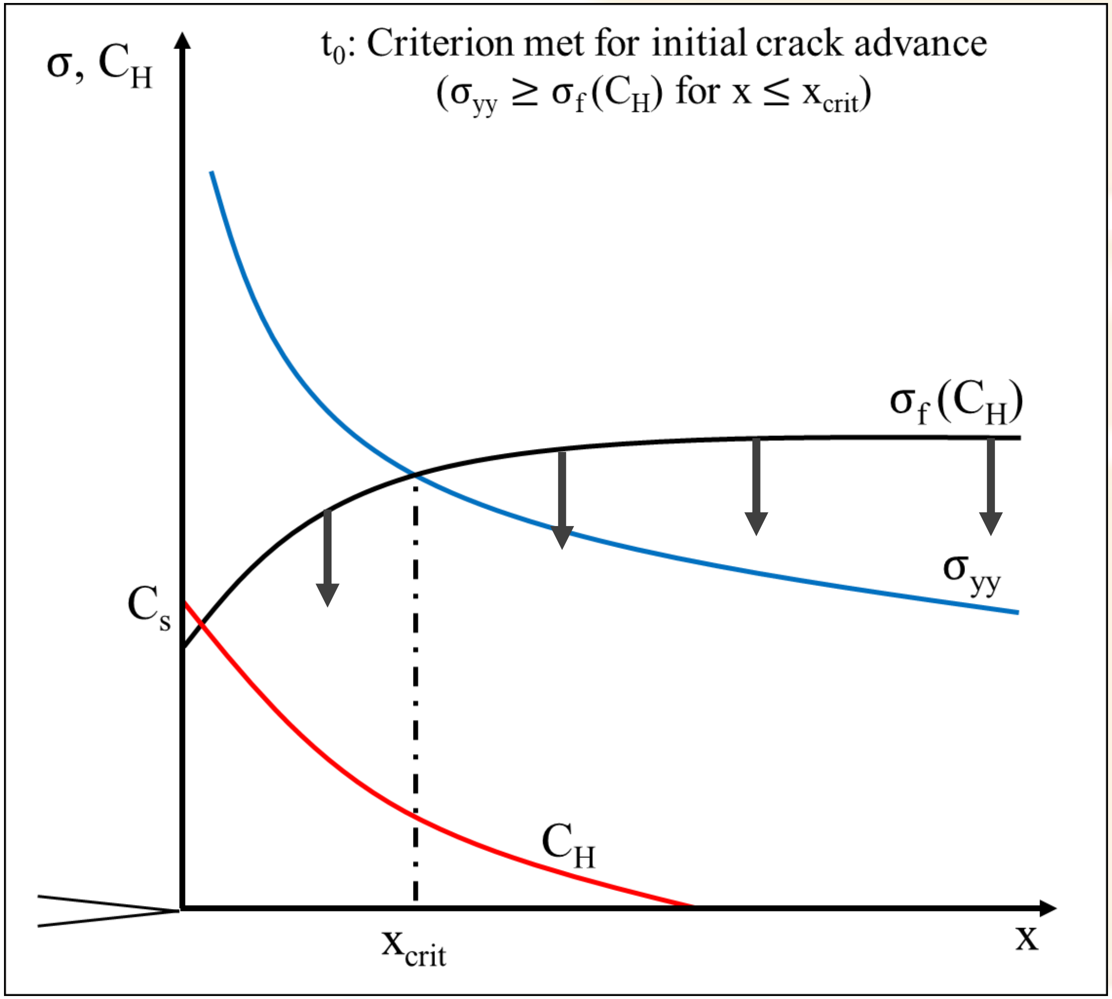
4. Modify $\sigma_f(C_H)$

Material

- *Aging/Plate thickness*
- *GB PPC spacing/geometry*
- *GB segregation*
- *PFZs*

Environment

- *N/A*



Material/Environmental Sensitivities

Well-known phenomenological sensitivities can be rationalized in this paradigm

4. Reduce

Mat
- *Ag*
- *GB P*
  spa
- *GB s*
- *PFZs*

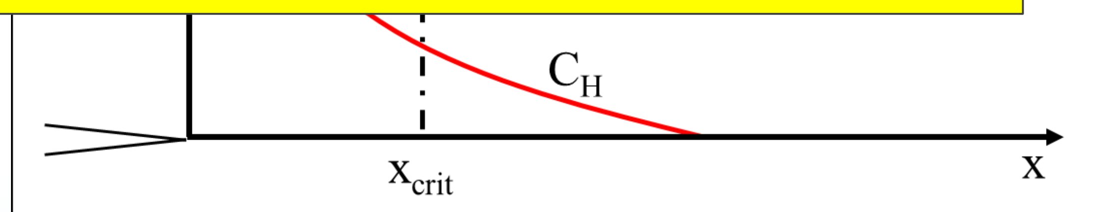
Env
- *N/A*

Why do these things matter??

- *To properly design testing approaches and protocols it is imperative to holistically understand the damage process*

(RH vs water content example…)

- *Demonstrates multi-faceted nature of the damage physics;* ***difficult to make conclusions if not all variables are controlled!!!***



Testing Approaches

Testing Approaches

Characteristics of a Good EAC Test:

- *Clear definition of testing goals*
  - *Screening? Qualification? Modeling? Mechanistic understanding?*
- *If transferability to application is desired*
  - *Environmental similitude*
    - *Or purposely selected bounding environment*
  - *Mechanical similitude (LEFM)*
    - *Does NOT exist for "bulk stress thresholds"*
- *Careful control/monitoring of environment*
- *Isolation of variables*
  - *Metallurgical, environmental mechanical*

Testing Approaches

- ***Legacy*** *(Total Life)*
  - *Qualification/Screening*
  - *ASTM G129 (SSRT) and G49 (Tensile)*
  - *ASTM G44 and G47 (3.5% NaCl, Alt Immersion)*
  - *Criteria: Failure/damage observation/reduction on ductility*
  - ***Any "threshold" has no mechanical/environmental similitude!!!***
- ***EASA SIB 2018-04R2*** *(Total Life)*
  - *Screening*
  - *ASTM G49 (70C, 85% RH, 85% YS)*
  - *Criteria: damage observation*
- ***LEFM Testing*** *(Crack Propagation)*
  - *ASTM E1681, G168, etc.*

Testing Approaches

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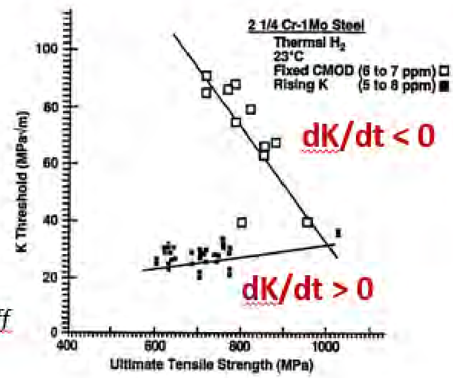
- ***LEFM Testing*** *(Crack Propagation)*
  - *ASTM E1681, G168, etc.*

Note: Details of the LEFM testing MATTERS!!!!

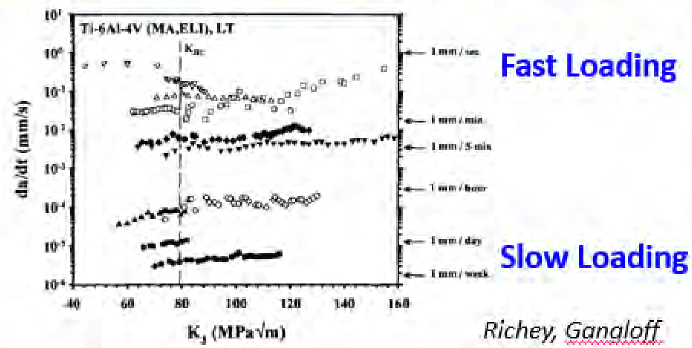
Testing Approaches: Detour

LEFM EAC behavior is known to depend on loading rate, however current LEFM testing do not control the loading rate

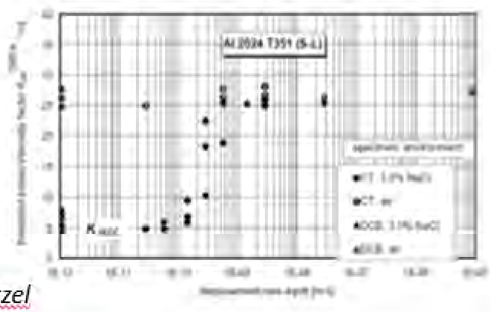
It is well known that variations in loading rate can affect EAC susceptibility



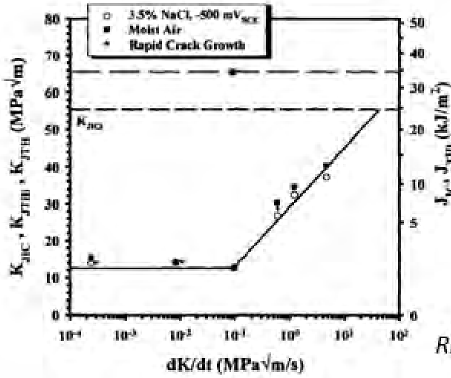
Gangloff



Richey, Gangloff



Dietzel



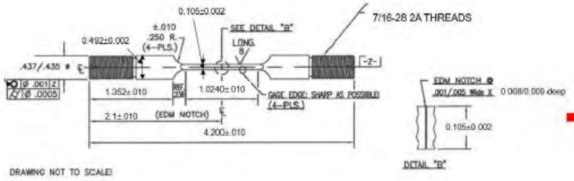
Richey, Gangloff

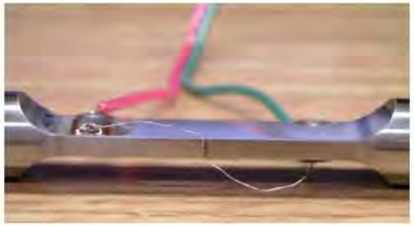
Testing Approaches: Detour

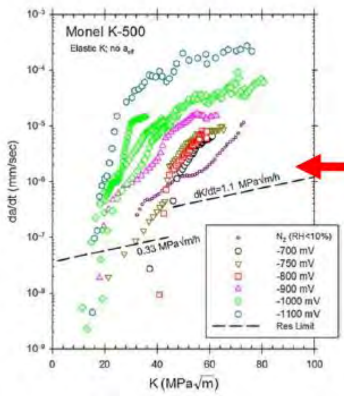
- ***ASTM EAC Testing Standard is Being Developed…***
  - *Rising K, active crack length monitoring (dcPD), environmental flexibility, testing design to conform to LEFM constraints*

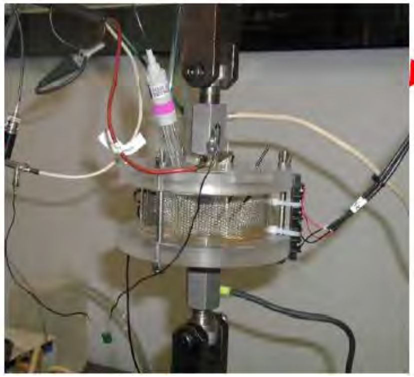
Fracture mechanics-based method for assessing EAC behavior

Utilize dcPD-based crack length measurements to enable K-controlled testing of specimens exposed to an applied potential while immersed in 0.6 M NaCl





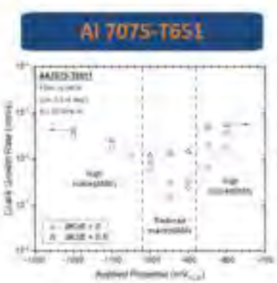


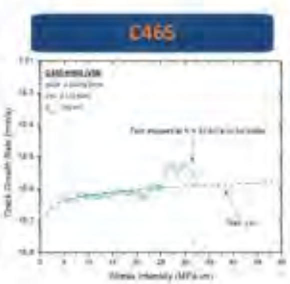


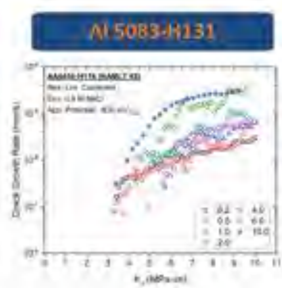
Testing Approaches: Detour

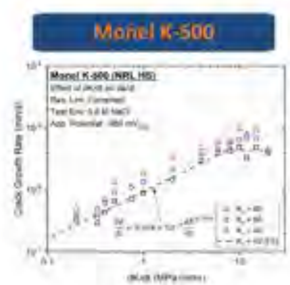
- **ASTM EAC Testing Standard is Being Developed…**
  - Explored for a wide-range of materials and environments
    - **Strength, Oxide stability, Mechanism (HE vs AD), Toughness, Diffusivity**

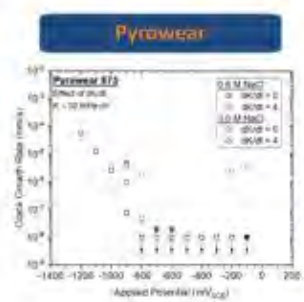
Alloy Class	Pertinent Material Properties
AA7075-T651	Coupled corrosion-hydrogen mechanism, modest strength, slow H diffusivity
AA5456-H116	Coupled corrosion-hydrogen mechanism, low strength, slow H diffusivity
Monel K-500	No oxide under in-service conditions, moderate strength, slow H diffusivity
C465/Pyrowear	Very high strength, modest H diffusivity
Beta-C Ti	Strong passive film, high strength, fast H diffusivity
316L	AD/HE mechanism, low strength, slow H diffusivity

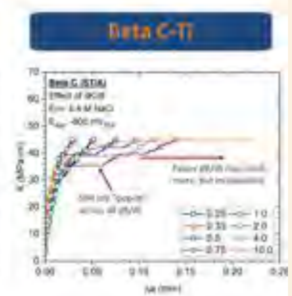












Testing Approaches: Detour

- **ASTM EAC Testing Standard is Being Developed…**

Take-Away

- *In all cases rising-K (dK/dt > 0 MPa√m) is:*
  - **CONSERVATIVE**
  - **More Efficient (done in <1 week)**

ASTM E1681

steels ($_{YS}$< 1,200 MPa)	10 000 hours
steels ($_{YS}$> 1,200 MPa)	5 000 hours
aluminum alloys	10 000 hours
titanium alloys	1 000 hours

Pertinent Publications

- **Monel K-500:**
  - **Z.D. Harris**, E.M. Dubas, A.S Popernack, B.P. Somerday, and J.T. Burns, "Elucidating the loading rate dependence of hydrogen environment-assisted cracking in a Ni-Cu superalloy", *Theoretical and Applied Fracture Mechanics*, p. 102846, 2021.
- **7xxx-Al:**
  - **Z.D. Harris** and J.T. Burns, "The effect of loading rate on the environment-assisted cracking behavior of AA7075-T651 in aqueous NaCl solution", *Corrosion and Materials Degradation*, vol. 2, p. 360-375, 2021.
- **5xxx-Al:**
  - **Z.D. Harris** and J.T. Burns, "On the loading rate dependence of environment-assisted cracking of sensitized AA5456-H116 exposed to marine environments", *Corrosion Science,* vol. 201, p. 110267, 2022.
- **High Strength Steel:**
  - **Z.D. Harris**, R.S. Marshall, R.G. Kelly, and J.T. Burns, "Coupling Fracture Mechanics Experiments and Electrochemical Modeling to Mitigate Environment-Assisted Cracking in Engineering Components," *Corrosion Journal, 79(3), p. 363-375, 2023.*
  - R. S. Marshall, Z. D. Harris, M. K. Small, K. L. Brunner, J. T. Burns, R. G. Kelly, "A Materials Selection Framework for Fastener-in-Panel Geometries Using FEM and LEFM, to Mitigate Coating Degradation and Hydrogen Embrittlement", *Corrosion Science*, in review
- **Austenitic Stainless Steel:**
  - *S. Blust, J.T. Burns, "The effect of loading rate on the environmentally assisted cracking behavior of 304L", Corrosion Reviews, in review.*
- **Strain Induced Artifacts:**
  - **Z.D. Harris** and J.T. Burns, "Evaluation of strain-induced artifacts in crack length measurements via the direct current potential difference technique", in *ASTM STP 1638: Fifth Symposium on Evaluation of Existing and New Sensor Technologies for Fatigue, Fracture, and Mechanical Testing*, P. McKeighan, ed., *138–159.* http://doi.org/10.1520/STP163820210046, *2022.*
- **In preparation:**
  - **Beta Titanium**
  - **Custom 465**

Testing Approaches

Why did legacy screening approaches not capture this EAC issue with 3rd generation alloys?

Testing Approaches

- ***Issue?***
  - **Not the right combination of accelerating factors for some alloys and some structures (Example: ASTM G34 for Al-Li)**

Testing Approaches

- ***Issue?***
  - **Total Life Approach…**

Testing Approaches

- *Issue?*
  - Total Life Approach…

Total Life =

Time for Step 1: Precursor development

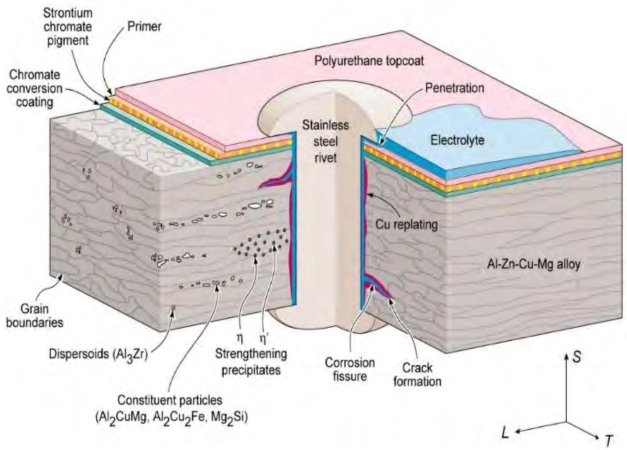
\+ Time for Step 2: Crack initiation

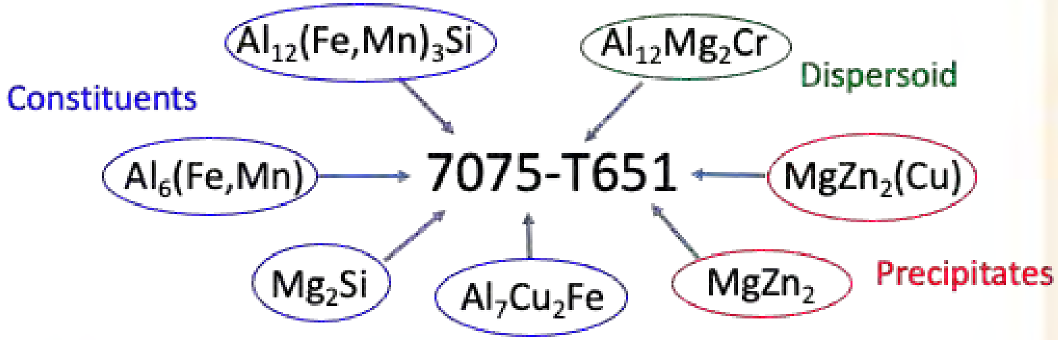
\+ Time for Step 3: Small crack growth

\+ Time for Step 4: Long crack growth

Testing Approaches

- *Issue?*
  - **Total Life Approach…**





Total Life =

Time for Step 1: Precursor development

+ Time for Step 2: Crack initiation

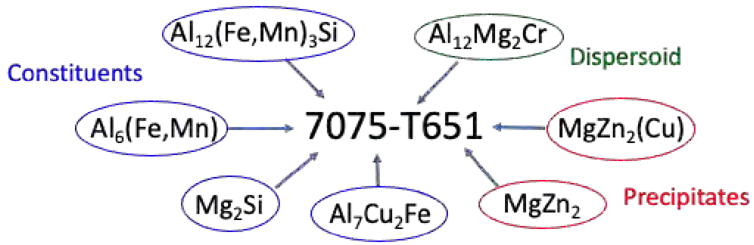
+ Time for Step 3: Small crack growth

+ Time for Step 4: Long crack growth

In a "Total Life" NaCl test the pre-cursor development and crack initiation is from corrosion at constituent particles

Testing Approaches

- ***Issue?***
  - **Total Life Approach…**



	7050	7085
Component Elements	**Metric**	**Metric**
Aluminum, Al	87.3 - 90.3 %	87.62 - 90.42 %
Chromium, Cr	<= 0.04 %	<= 0.04 %
Copper, Cu	2.0 - 2.6 %	1.3 - 2.0 %
Iron, Fe	<= 0.15 %	<= 0.08 %
Magnesium, Mg	1.9 - 2.6 %	1.2 - 1.8 %
Manganese, Mn	<= 0.10 %	<= 0.04 %
Other, each	<= 0.05 %	<= 0.05 %
Other, total	<= 0.15 %	<= 0.15 %
Silicon, Si	<= 0.12 %	<= 0.06 %
Titanium, Ti	<= 0.06 %	<= 0.06 %
Zinc, Zn	5.7 - 6.7 %	7.0 - 8.0 %
Zirconium, Zr	0.08 - 0.15 %	0.08 - 0.15 %

Total Life =

Time for Step 1: Precursor development

+ Time for Step 2: Crack initiation

+ Time for Step 3: Small crack growth

+ Time for Step 4: Long crack growth

7085 would be expected to have fewer constituent particles due to composition; thus slower Step 1 and 2

Testing Approaches

- ***Issue?***
  - **Total Life Approach…**

Total Life =

Time for Step 1: Precursor development

+ Time for Step 2: Crack initiation

+ Time for Step 3: Small crack growth

+ Time for Step 4: Long crack growth

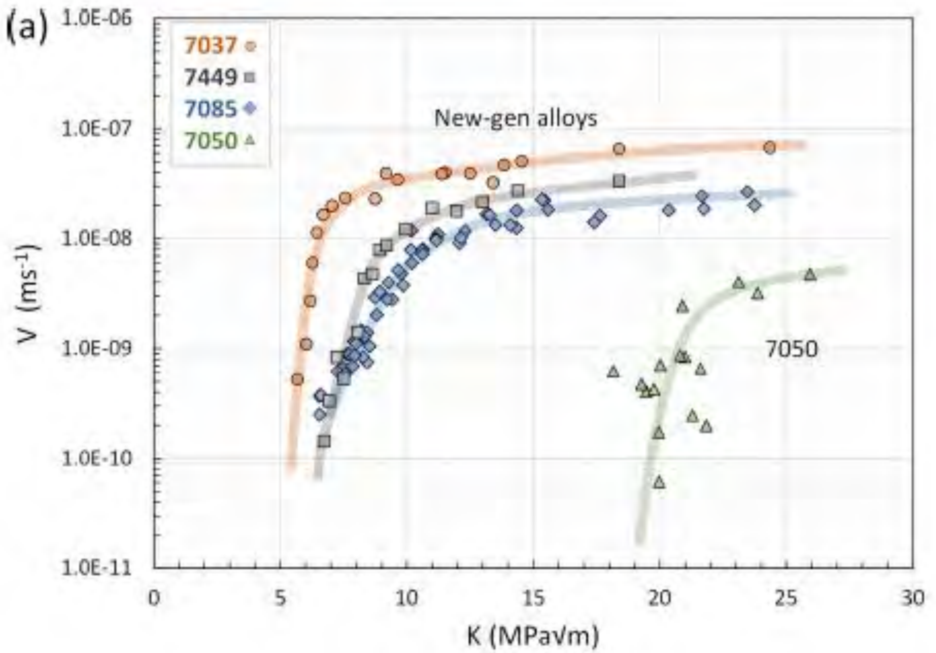


Fig. 7. Decreasing stress intensity-growth rate (v-K) curves from the DCB tests conducted on the new-gen alloys, compared to benchmark data for AA7050-T7651 (tested at 70 °C and 85 % RH) presented as; (a) a conventional logarithmic and (b) a linear v - K plot. Overlaid data is shown for 4 tests from each material (apart from AA7449-T7651; 3 tests). The materials tested were: AA7050-T7651, 140 mm plate; AA7085-T7651, 150 mm plate, AA7449-T7651, 95 mm plate, AA7037-T7452, 136 mm forged plate.

The slower development of Step 1 and 2 could have masked the faster crack growth (Step 3)

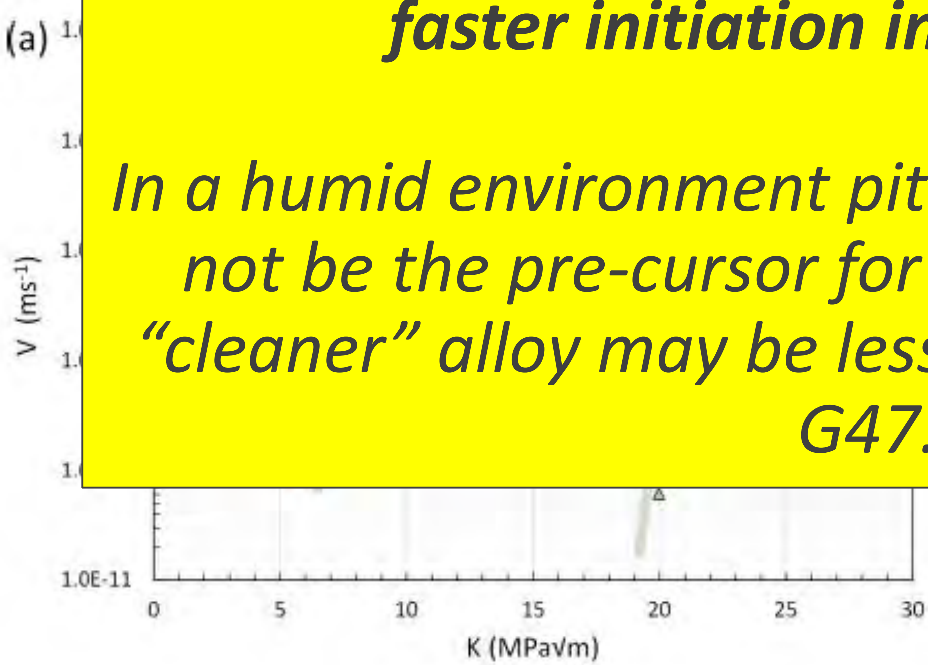
Testing Approaches

Total Life =

- ***Issue?***

What about Zak Barrett's Airbus data showing faster initiation in 85% RH, 70C?

In a humid environment pitting at constituents may not be the pre-cursor for crack initiation so the "cleaner" alloy may be less relevant than in ASTM G47…



n

growth

o

masked the faster crack growth (Step 3)

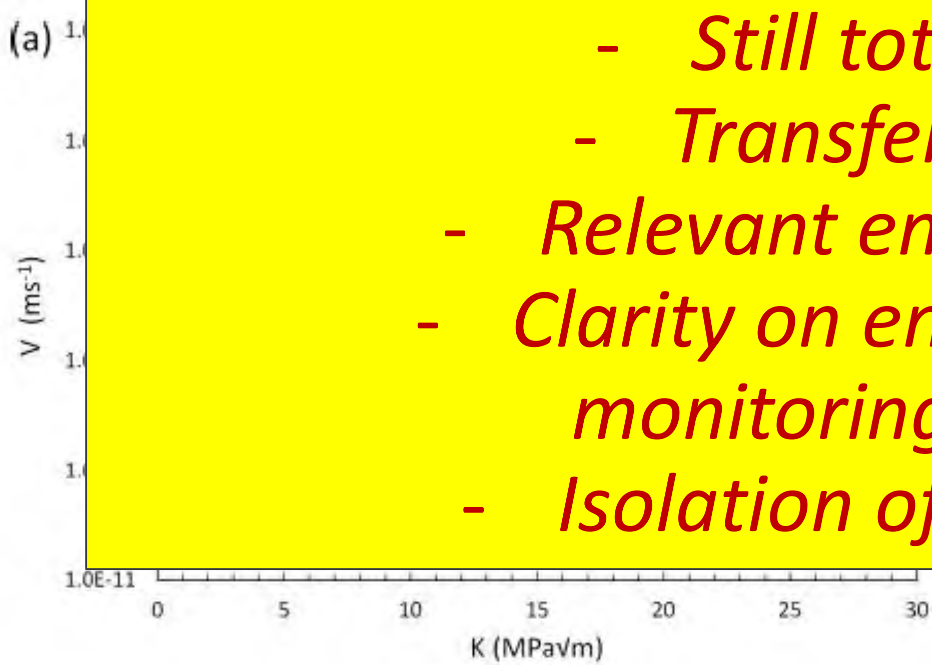
Fig. 7. Decreasing stress intensity-growth rate (v-K) curves from the DCB tests conducted on the new-gen alloys, compared to benchmark data for AA7050-T7651 (tested at 70 °C and 85 % RH) presented as; (a) a conventional logarithmic and (b) a linear v - K plot. Overlaid data is shown for 4 tests from each material (apart from AA7449-T7651; 3 tests). The materials tested were: AA7050-T7651, 140 mm plate; AA7085-T7651, 150 mm plate, AA7449-T7651, 95 mm plate, AA7037-T7452, 136 mm forged plate.

Schwarzenbock, Corr Sci, 2020

Testing Approaches

Total Life =

- ***Issue?***



Does the EASA Approach Fix This?

- *Still total life…*
- *Transferability?*
- *Relevant environment?*
- *Clarity on environmental monitoring/controls?*
- *Isolation of variables?*

n

growth

o

crack growth (Step 3)

Fig. 7. Decreasing stress intensity-growth rate (v-K) curves from the DCB tests conducted on the new-gen alloys, compared to benchmark data for AA7050-T7651 (tested at 70 °C and 85 % RH) presented as; (a) a conventional logarithmic and (b) a linear v - K plot. Overlaid data is shown for 4 tests from each material (apart from AA7449-T7651; 3 tests). The materials tested were: AA7050-T7651, 140 mm plate; AA7085-T7651, 150 mm plate, AA7449-T7651, 95 mm plate, AA7037-T7452, 136 mm forged plate.

Summary of Questions and Needs

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- **Testing Improvement**
  - *Total life approach may mask important sensitivities*
  - *Ensure capturing water content rather than RH*
  - *Target relevant mechanism with testing*
  - *Ensure testing approach matches goals (screening, mechanistic, etc)*
  - *Employ active loading rate for LEFM testing*

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  - *Target relevant mechanism with testing*
  - *Ensure testing approach matches goals (screening, mechanistic, etc)*
  - *Employ active loading rate for LEFM testing*
  - ***Work to be done:***
    - *Quantitatively establish the issues beyond hypotheses*
    - *Do we have the solution…learn from Fatigue!!!!!*
      - *Exposure (G44/47) for initiation/MSC*
      - *LEFM characterization of growth*
      - ***$1M Question: What environment???***

Summary of Questions and Needs

- **Engineering definition of environmental bounds**
  - *Reduce the research space to targeted environments and temps*

  - ***Work to be done:***
    - *Input from users*
    - *Identify relevant, differentiating, bounding cases; do not be paralyzed capturing every condition. Just the right ones…*
    - *Develop a correlation between the environment and the H-uptake*

Summary of Questions and Needs

- **Understanding the relative impact of the precursor, initiation, MSC, and long crack growth**
  - *For both testing and for service life*

  - ***Work to be done:***
    - *Current research with AFRL targeted toward this*

Summary of Questions and Needs

- **Mechanistic understanding beyond phenomenology for propagation to enable management/material improvement**
  - *Identify microstructure and environment sensitivities for propagation*

Summary of Questions and Needs

- **Mechanistic understanding beyond phenomenology for propagation to enable management/material improvement**
  - *Identify microstructure and environment sensitivities for propagation*
  - ***Work to be done:***
    - *Prioritization of critical parameters that are governing the damage mechanism*
      - *Identify how those parameters will vary with common material specification and processing routes that are used (overage, composition, etc)*
    - *Work moving forward on this…*
      - *Thus far water content is more relevant than T*

Summary of Questions and Needs

- **Generation of propagation data to enable engineering management**
  - *What is needed/desired by the OEM and structural management community?*
    - *New material?*
    - *LEFM based data?*
    - *Mitigation strategies?*

Summary of Questions and Needs

- **Generation of propagation data to enable engineering management**
  - *What is needed/desired by the OEM and structural management community?*
    - *New material?*
    - *LEFM based data?*
    - *Mitigation strategies?*

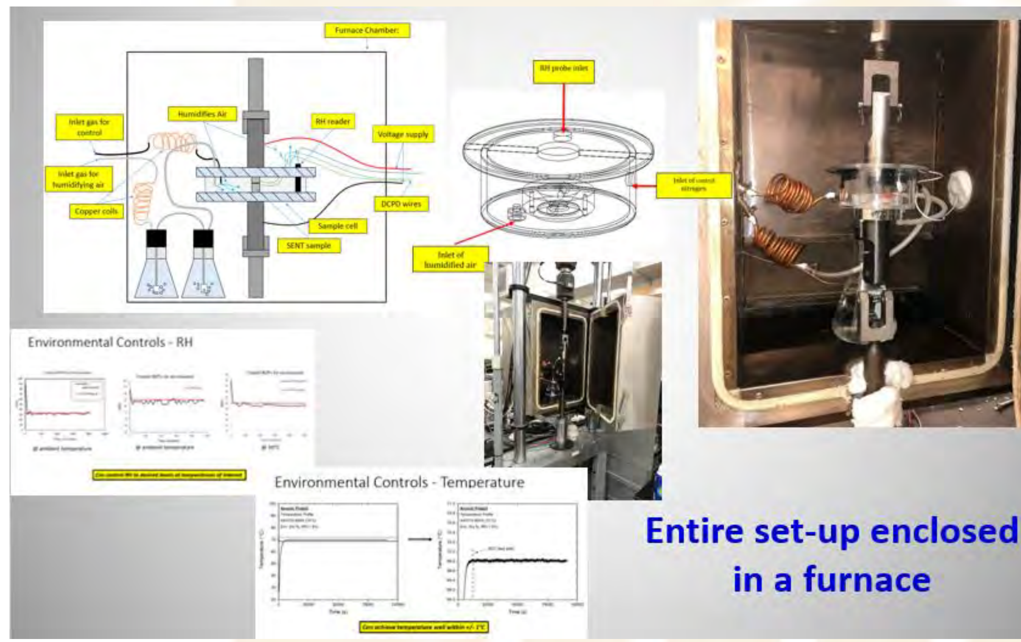
  - ***Work to be done:***
    - *Generation of relevant data for materials and environments that will help with life management*
    - *Exercising LEFM based models*

UVa Capabilities

- ***Electrochemistry expertise and equipment; Characterization facility***

- ***EAC testing capability and expertise***
  - *Full range of total life and LEFM testing*
  - *Full range of environmental control for elevated temp and humidity control*

- ***Experience linking EAC behavior to mechanism and causal microstructure feature***



- ***Extensive experience with EAC in 7xxx alloys***

- ***Ability to explore H-metal interactions***

UVa Capabilities

Mechanical Testing and Characterization Capabilities at University of Pittsburgh

Mechanical Testing

- **10 mechanical load frames** with ability to run compression, tension, fatigue, fatigue crack growth, fracture toughness, SSRT, and SCC experiments
- dcPD systems for **high-fidelity crack length monitoring** under wide range of environmental conditions
- **2 Charpy systems** (full size and sub-size)
- **Gleeble 3500 GTC** plus access to another Gleeble 3500 with custom high T kit for metallurgy studies

Materials Characterization

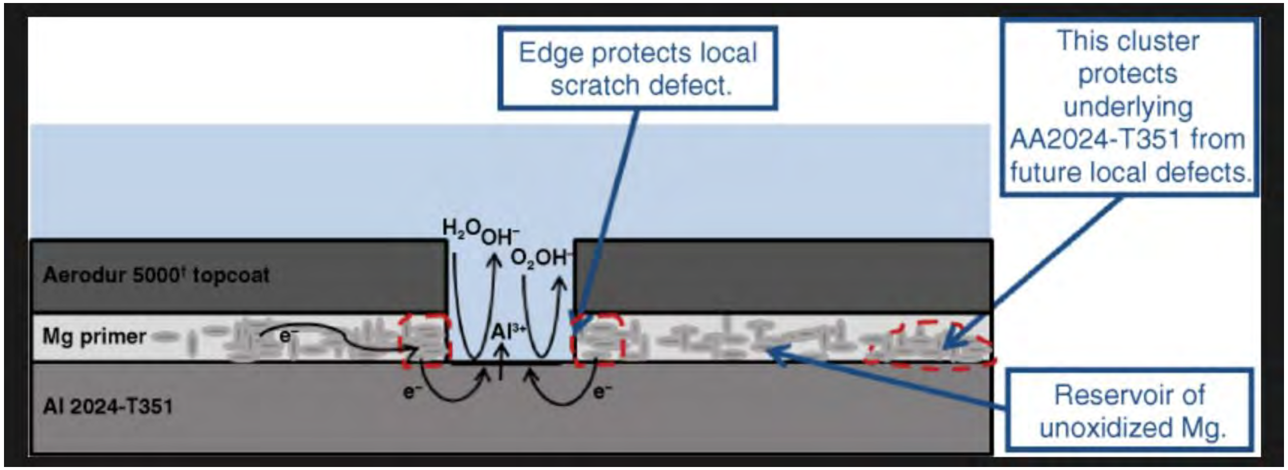
- 1 uCT with upgraded CMOS detector
- 3 XRDs
- 3 SEMs with upgraded EDS/EBSD
- 1 EPMA
- 1 FIB (with EDS/EBSD)
- 3 TEMs (environmental, metallurgy, and probe-corrected)
- 3 digital microscopes (including one with on-board LIBS)
- And others...

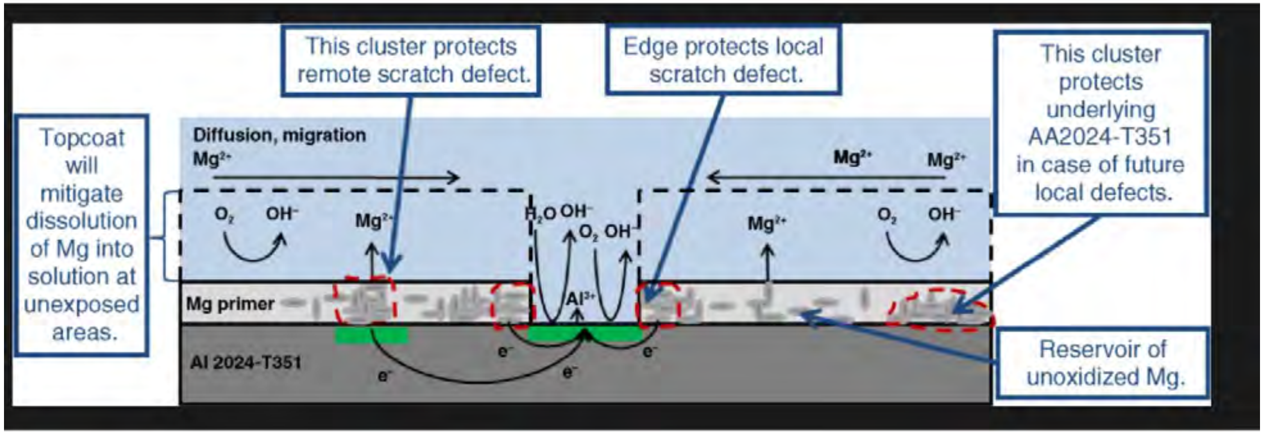
Experience leveraging these tools to establish mechanistic understanding of EAC in numerous materials, including 7xxx-series Al alloys

University of Pittsburgh | Swanson School of Engineering

Example

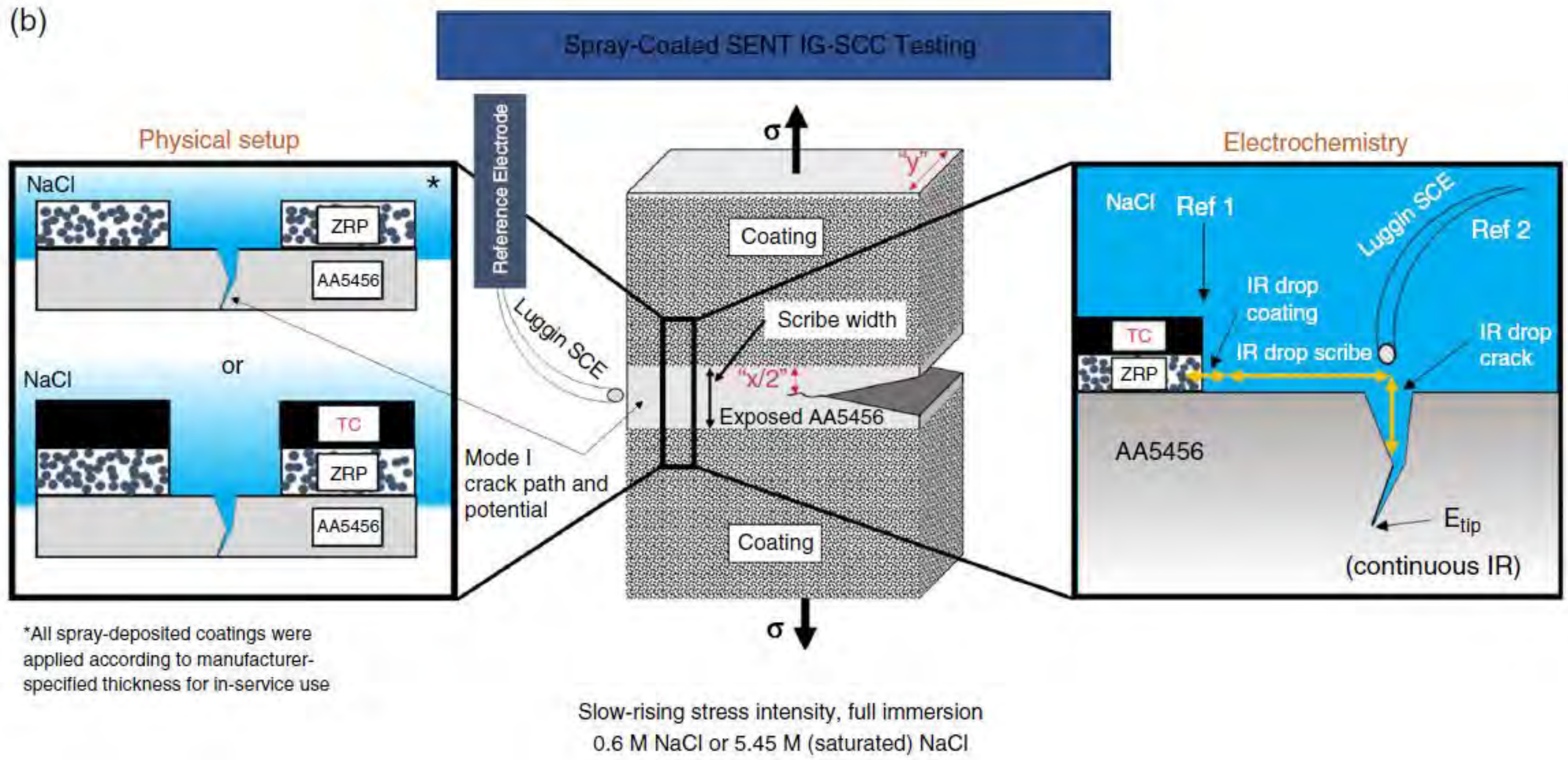
Metal-rich primer-based coatings that polarize the substrate has been demonstrated to be effective in mitigating CORROSION





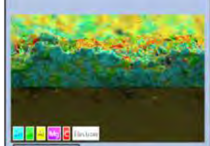
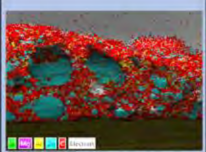
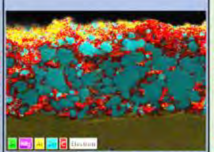
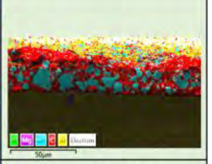
Metal-rich primer-based coatings that polarize the substrate has been demonstrated to be effective in mitigating and EAC

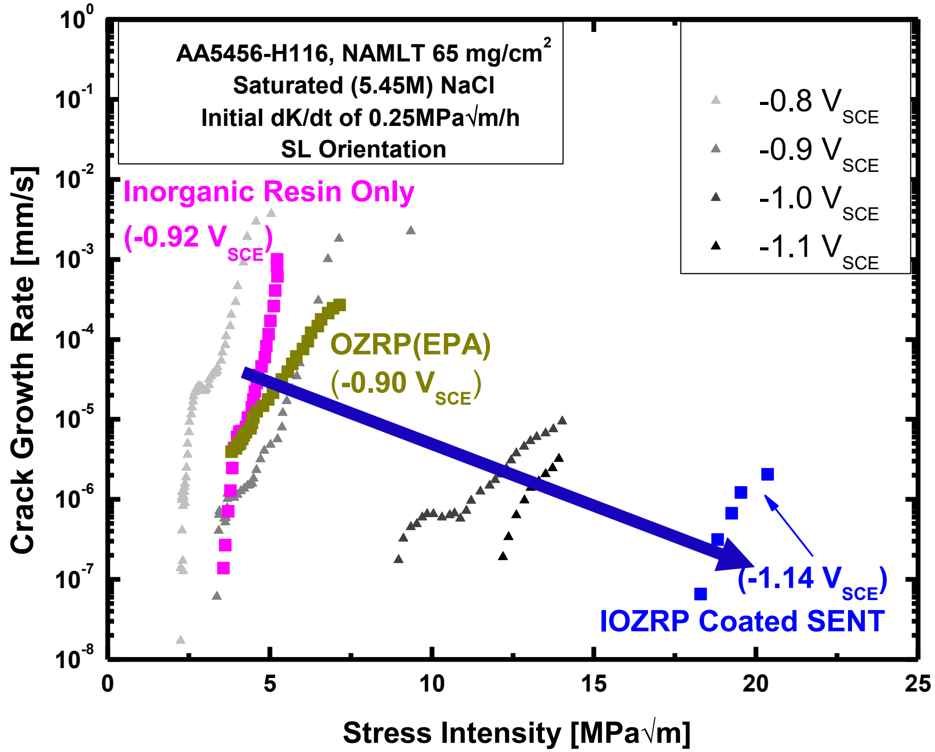
Example for 5xxx Al



Metal-rich primer-based coatings that polarize the substrate has been demonstrated to be effective in mitigating and EAC

Example for 5xxx Al

Sherwin Williams			NCP Coatings
83 Weight % Zn	85 Weight % Zn	90 Weight % Zn	90 Weight % Zn
76 Volume % Zn	65 Volume % Zn	57 Volume % Zn	83 Volume % Zn
IOZRP(EthylSil,76%)	**OZRP(EPA,65%)**	**OZRP(Epoxy,57%)**	**OZRP(U,83%)**
			
Inorganic ethyl silicate resin	Organic epoxy polyamide resin	Organic epoxy resin	Organic urethane resin



Vast Reduction in EAC Susceptibility due to "cathodic protection"

Some evidence that polarization via an MRP would be effective but very limited data for environments relevant to aerospace applications

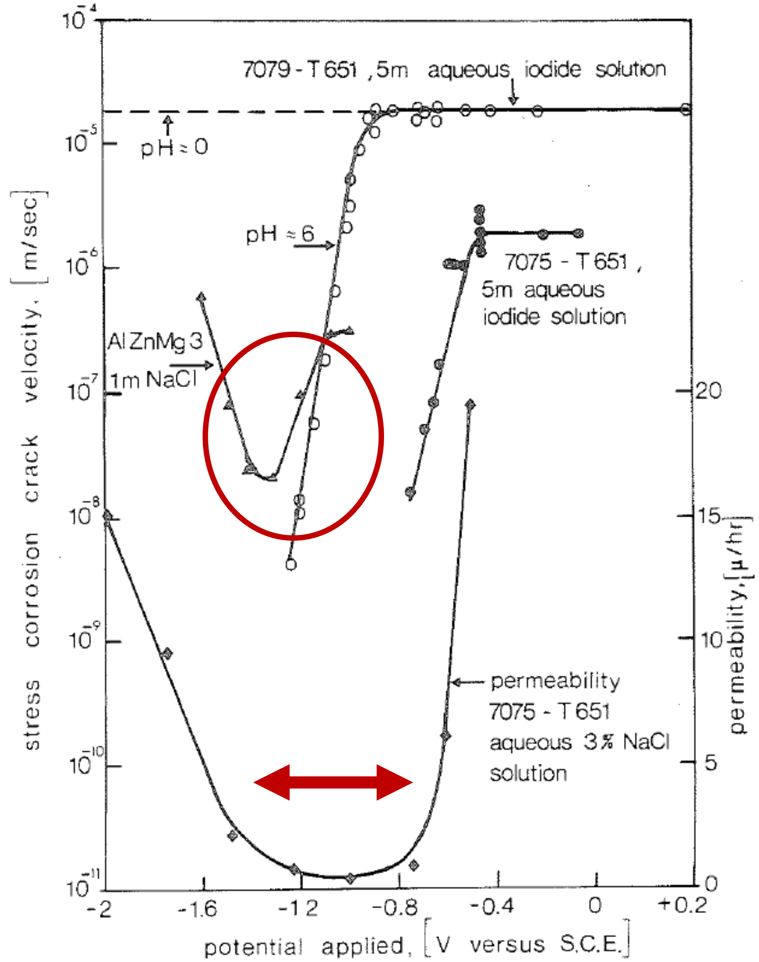


Fig. 10—Effect of electrical potential on hydrogen permeability and stress corrosion crack velocity in Al alloys.[25]

Speidel, 1975

Talk Objectives:

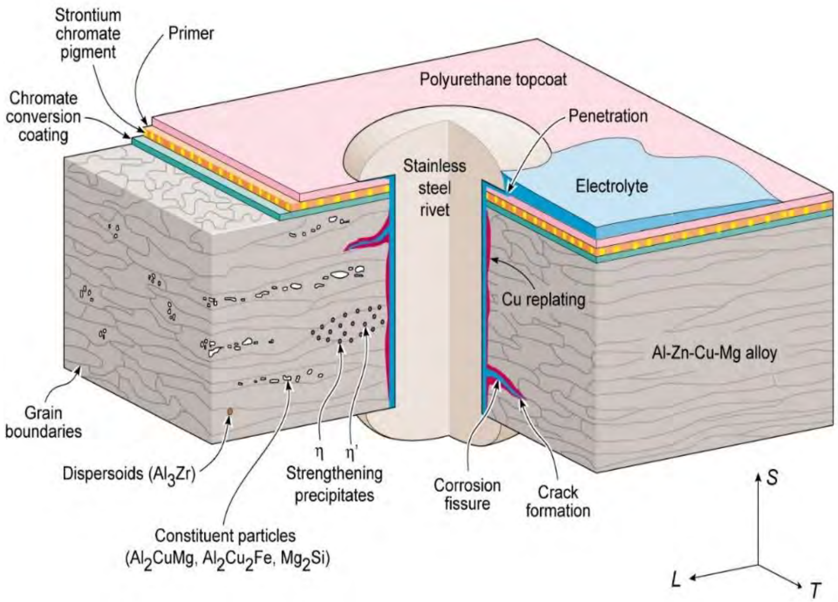
- ***Systematically characterize the EAC behavior of 7075-T651 and 7050-T7451 alloys as a function of applied potential***
  - *Establish what polarization levels would be desired for an MRP*

- ***Explore the mechanistic underpinnings of the observed behaviors***

- ***Use the data to explore the know variations in EAC behavior between alloy systems***

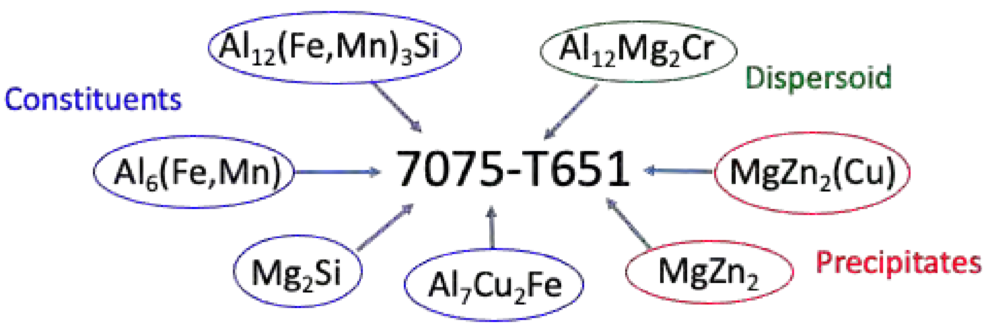
Alloys of Interest: AA7075-T651 and 7050-T7451

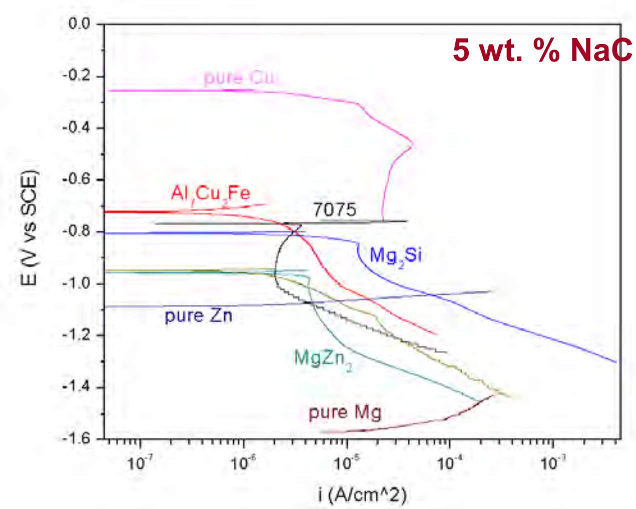
Complex microstructure representative of material utilized in aging aircraft



AA7075-T651		
Element	**Wt. %**	**7050**
Al	Bal.	
Zn	5.1-6.1	6.1
Cu	1.6	2.5
Mg	2.1-2.9	2.2
Fe	0.5	0.08
Si	0.4	0.02
Cr	0.18-0.28	
Ti	0.2	0.01

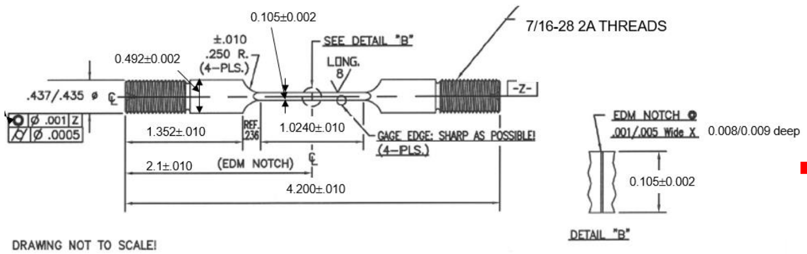
From Corrosion of Aluminum and Aluminum Alloys (Davis)

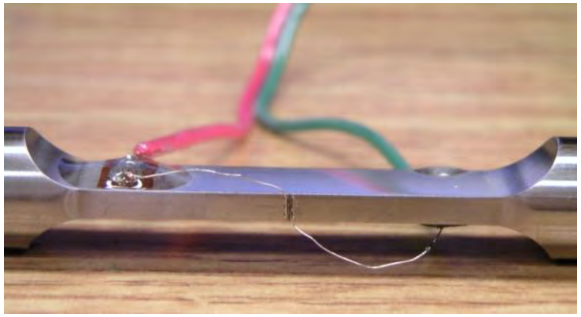


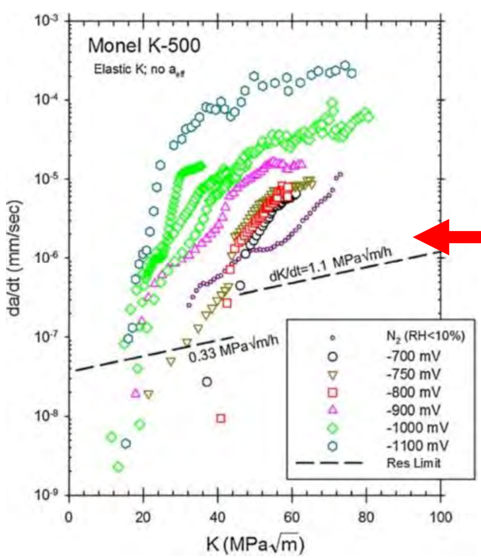


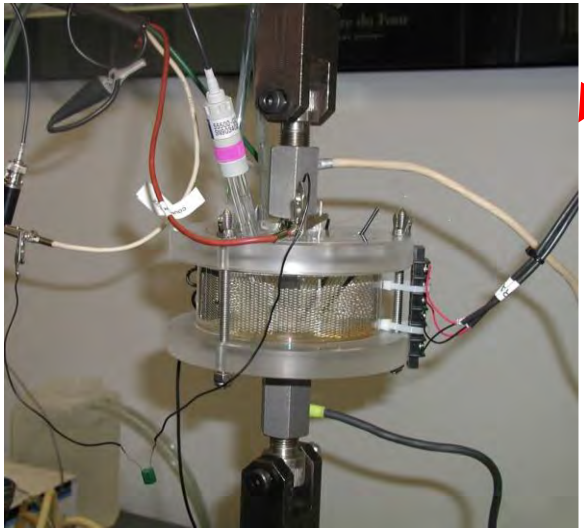
Fracture mechanics-based method for assessing EAC behavior

Utilize dcPD-based crack length measurements to enable K-controlled testing of specimens exposed to an applied potential while immersed in 0.6 M NaCl



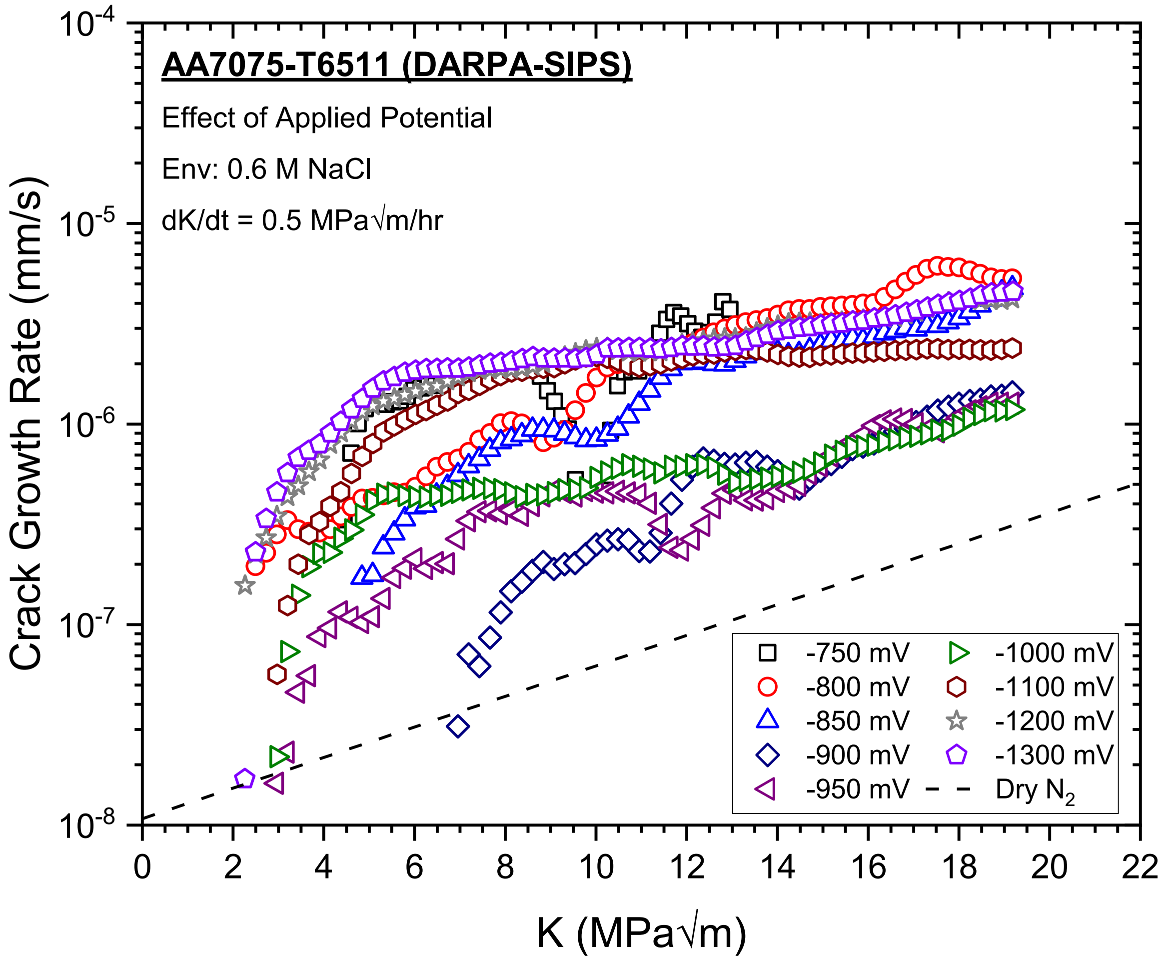




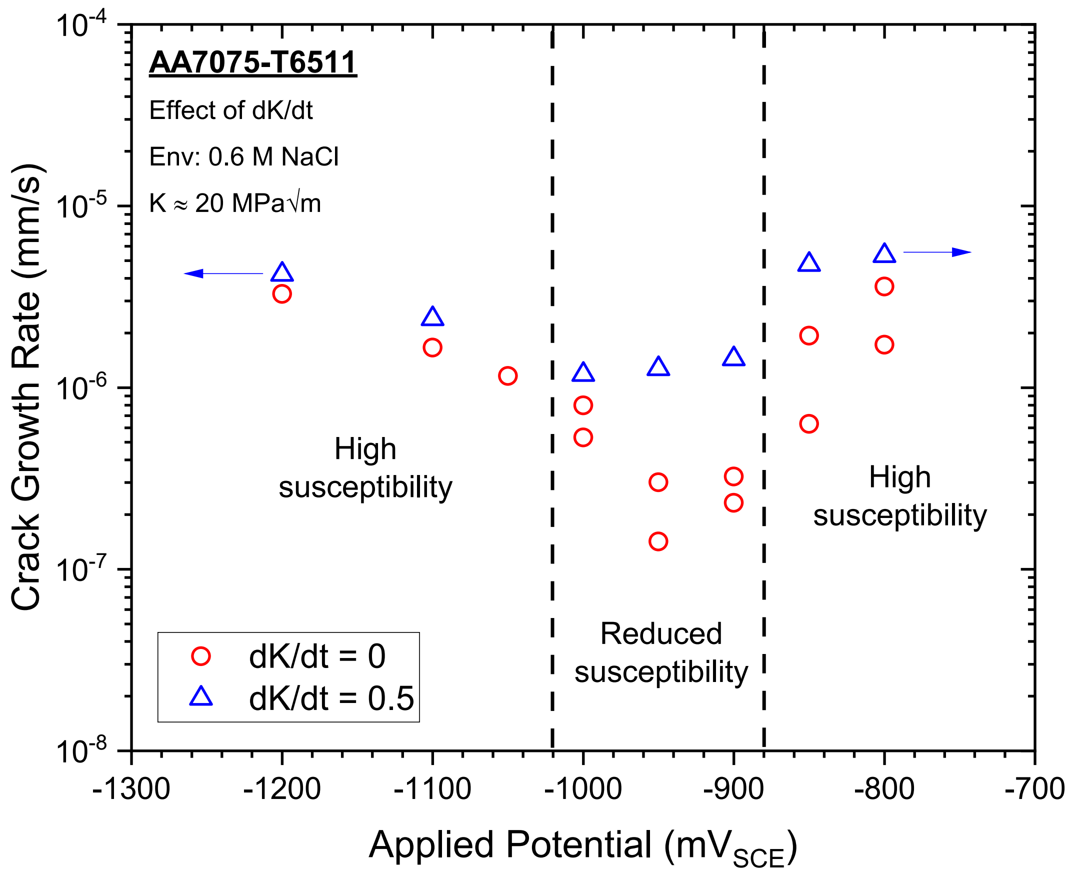


Gangloff et al., MMTA, 2014

Effect of applied potential on HEAC kinetics of AA7075-T6511

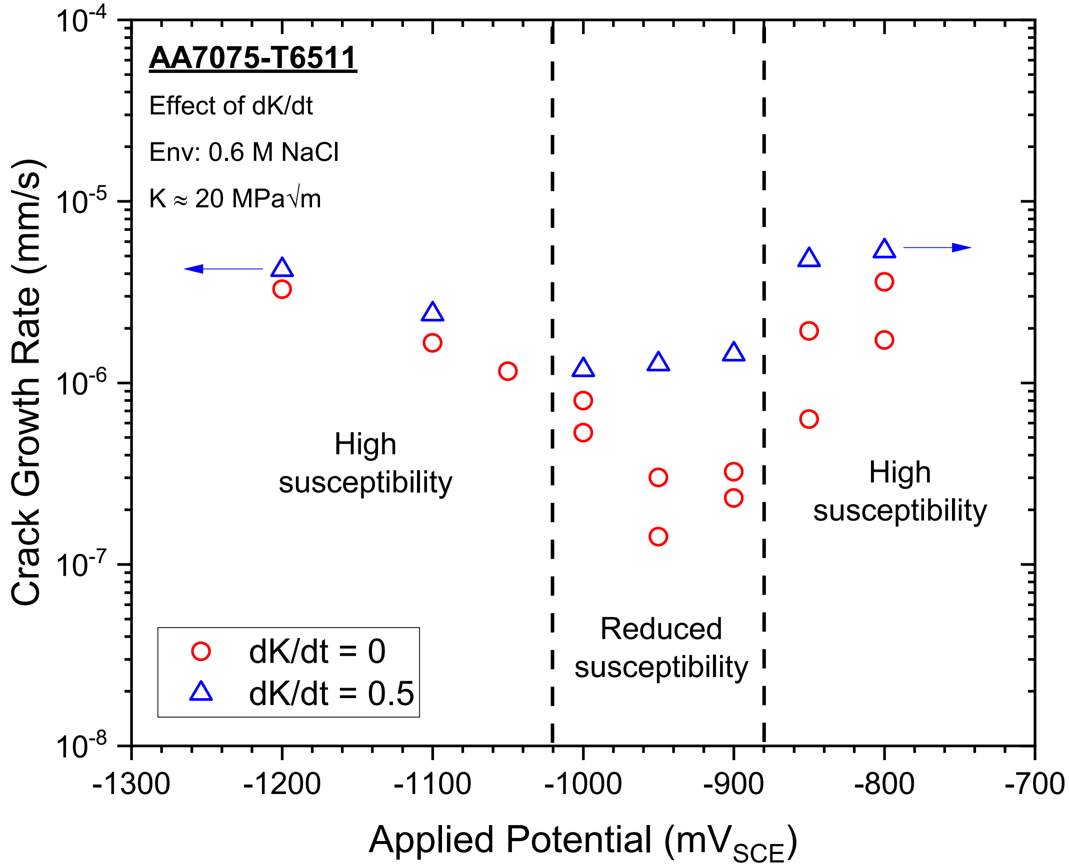


Can plot crack growth rate at iso-K to inform coating development



Observation 1: There is a region of reduced susceptibility

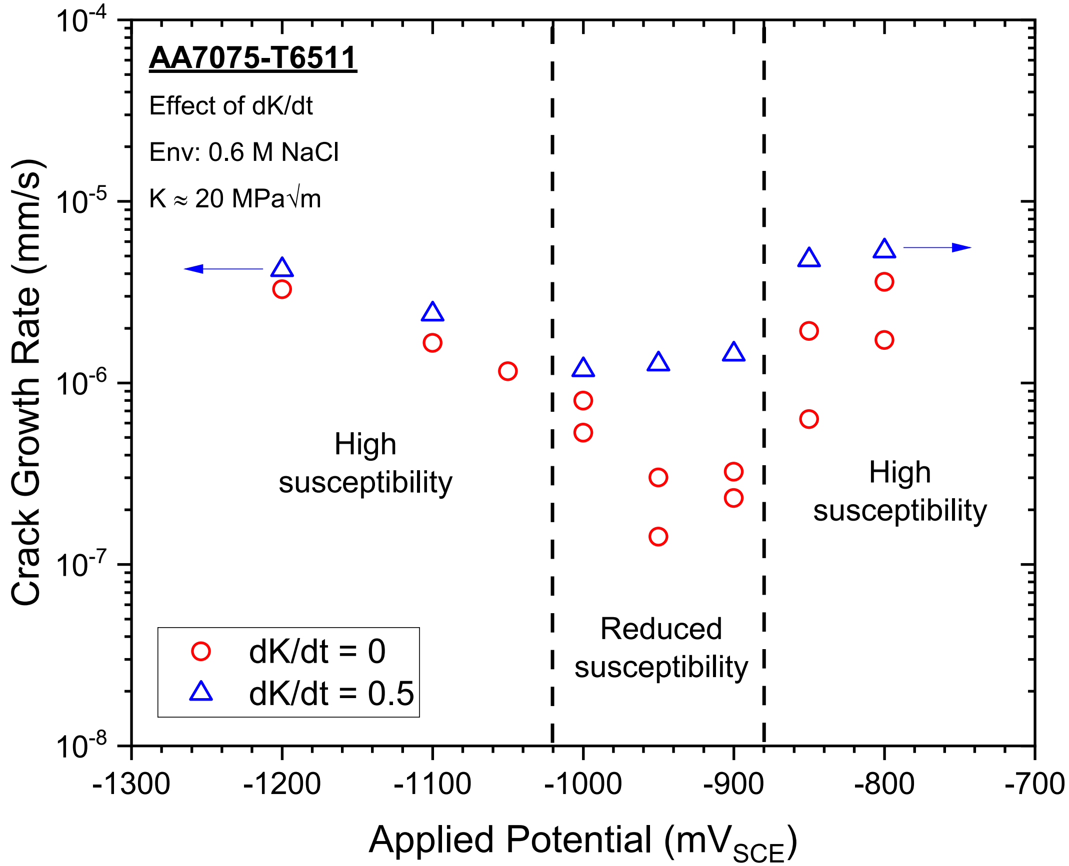
Can plot crack growth rate at iso-K to inform coating development



Observation 2: There is a loading rate dependence

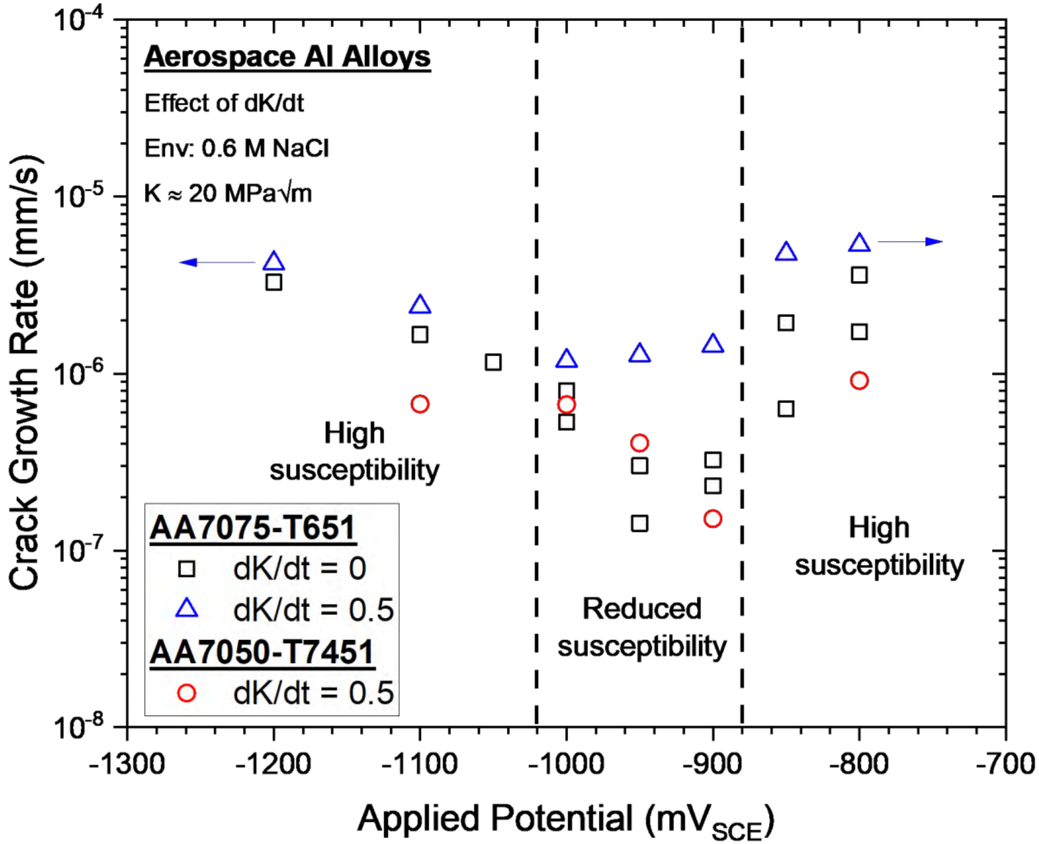
(Suggestions a strain-controlled process, not a stress-controlled process)

Can plot crack growth rate at iso-K to inform coating development

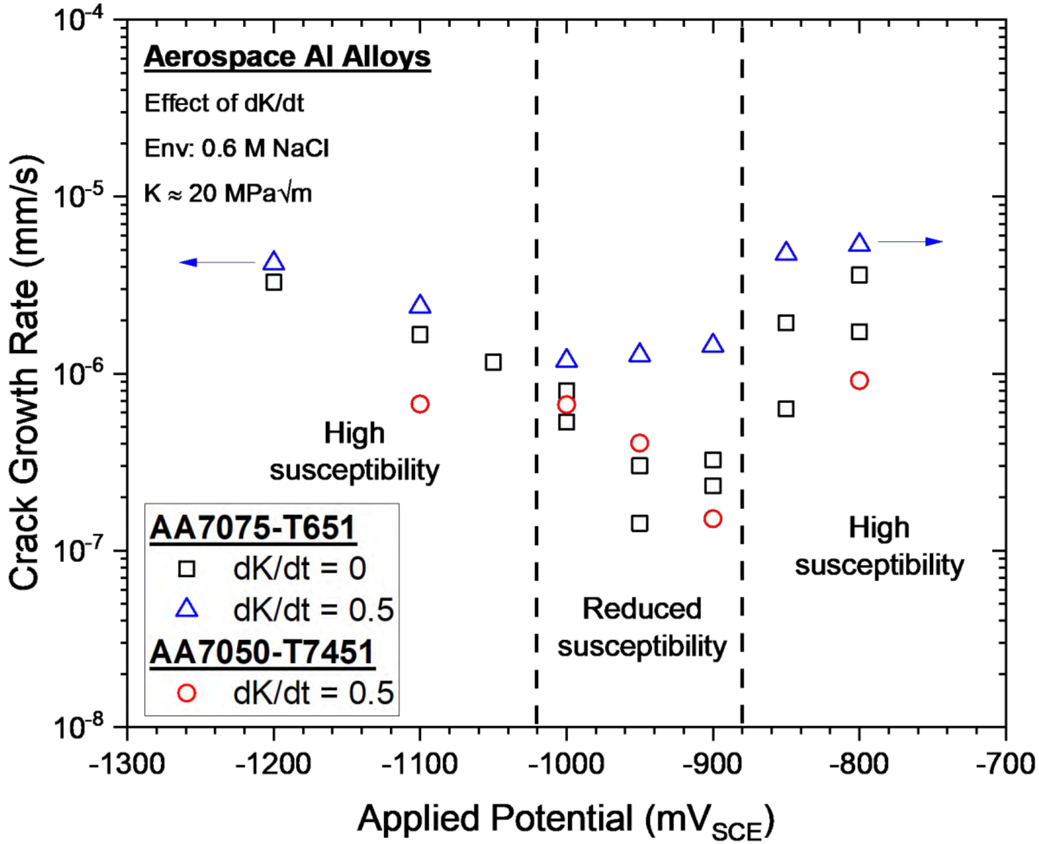


Observation 3: ***Cracking in the reduced susceptibility "well" is still very fast***

The same analysis was performed for 7050-T7451

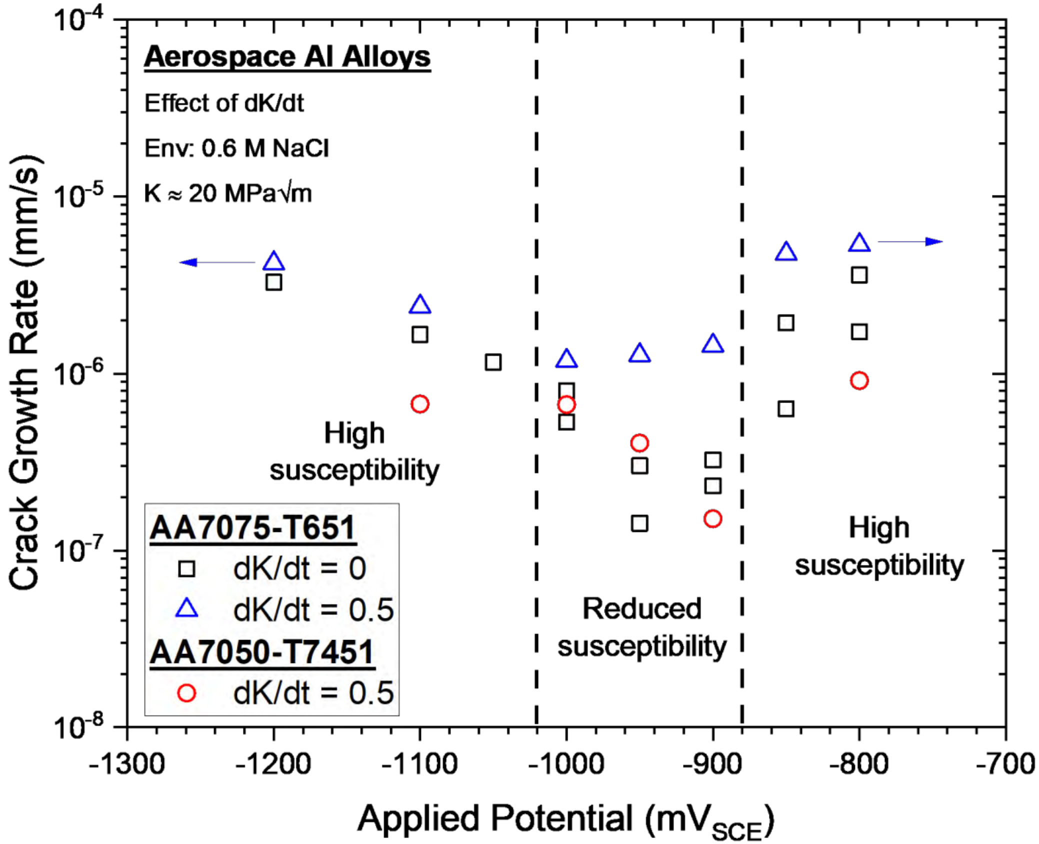


The same analysis was performed for 7050-T7451



Observation 1: As expected, 7050-T7451 (Higher Cu, OA) cracks substantially slower than 7075-T651

The same analysis was performed for 7050-T7451



Observation 2: 7050 exhibit reduced susceptibility "well" over the same potential range

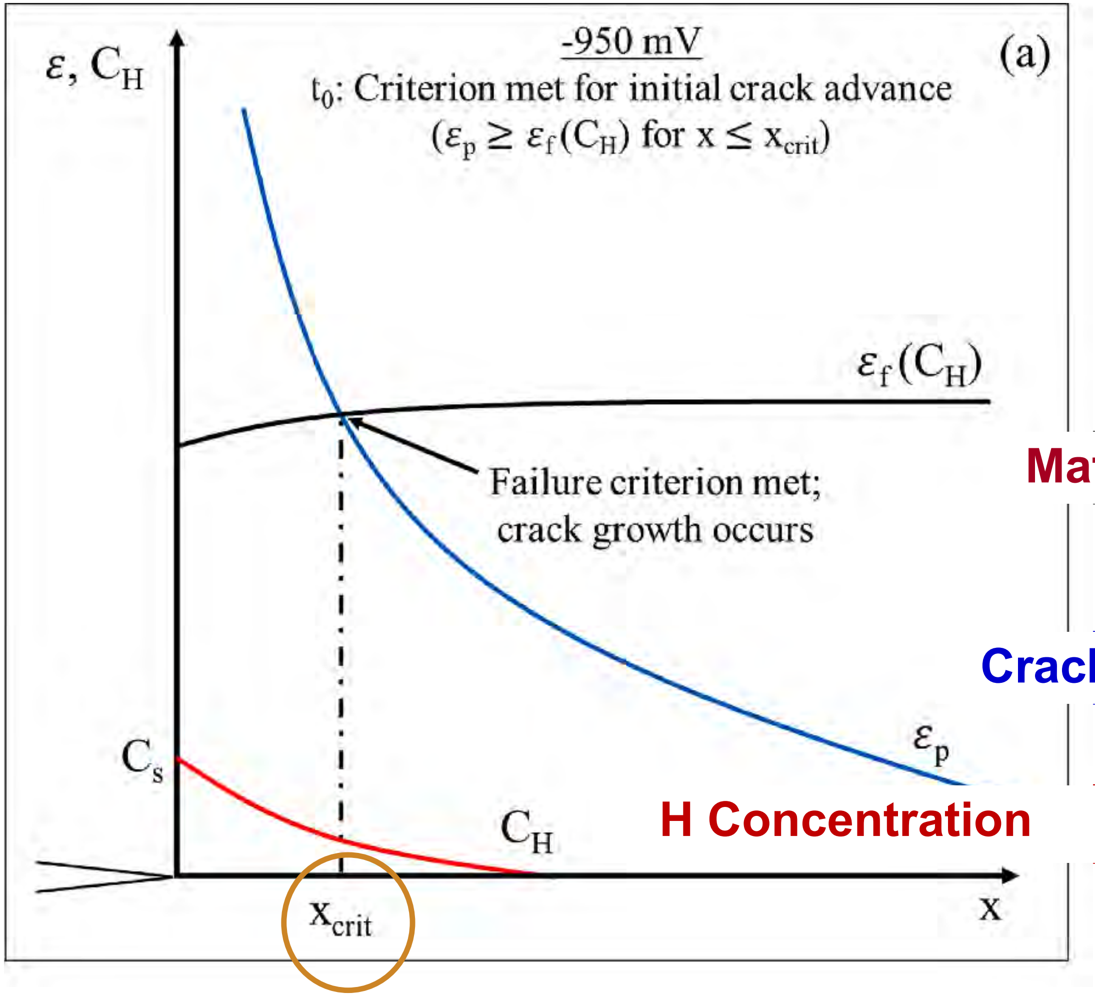
Talk Objectives:

- ***Systematically characterize the EAC behavior of 7075-T651 and 7050-T7451 alloys as a function of applied potential***
  - *Establish what polarization levels would be desired for an MRP*

- ***Explore the mechanistic underpinnings of the observed behaviors***

- ***Use the data to explore the know variations in EAC behavior between alloy systems***

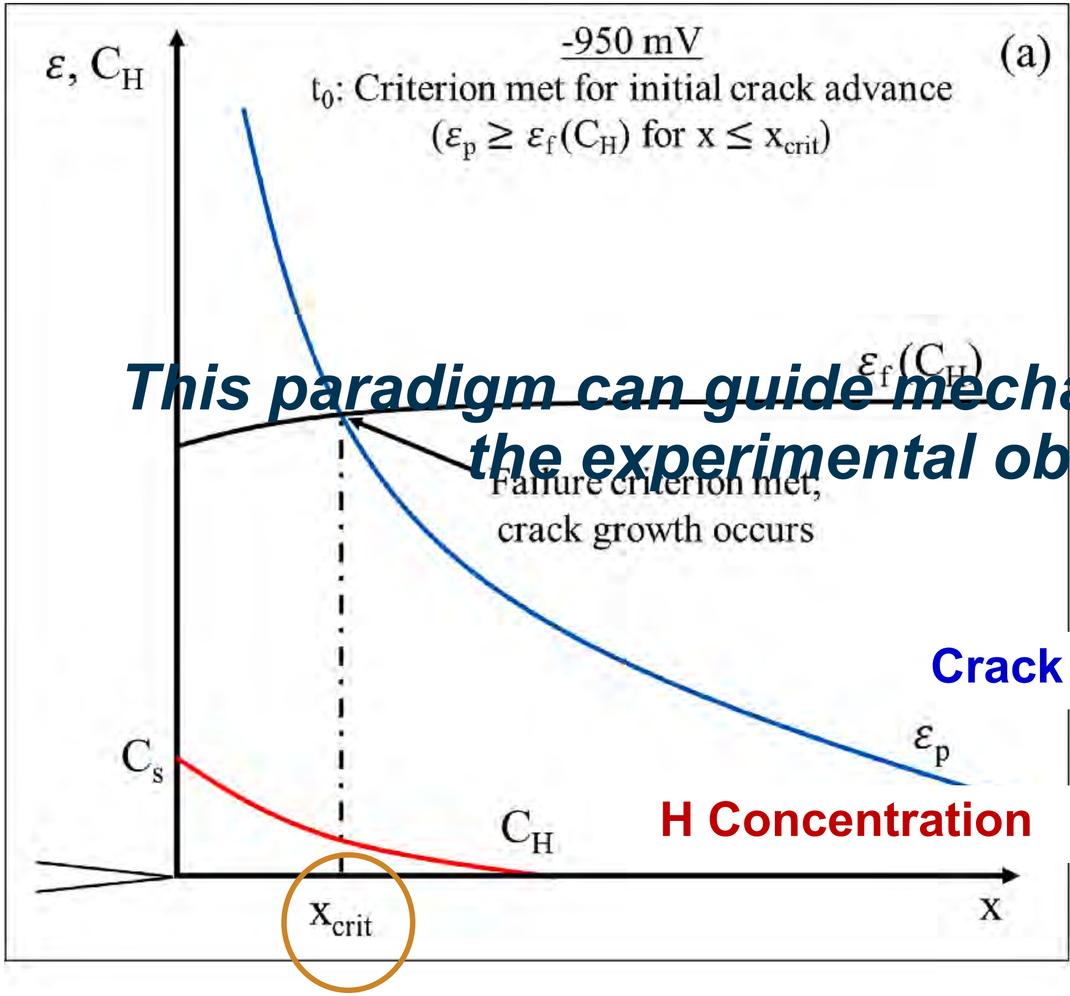
Mechanistic Paradigm for Strain Controlled HEAC



HEAC Analysis Paradigm
Ritchie-Thompson type damage model for strain-controlled crack advance

Strain must exceed material resistance over X_{crit} for crack advance

Mechanistic Paradigm for Strain Controlled HEAC

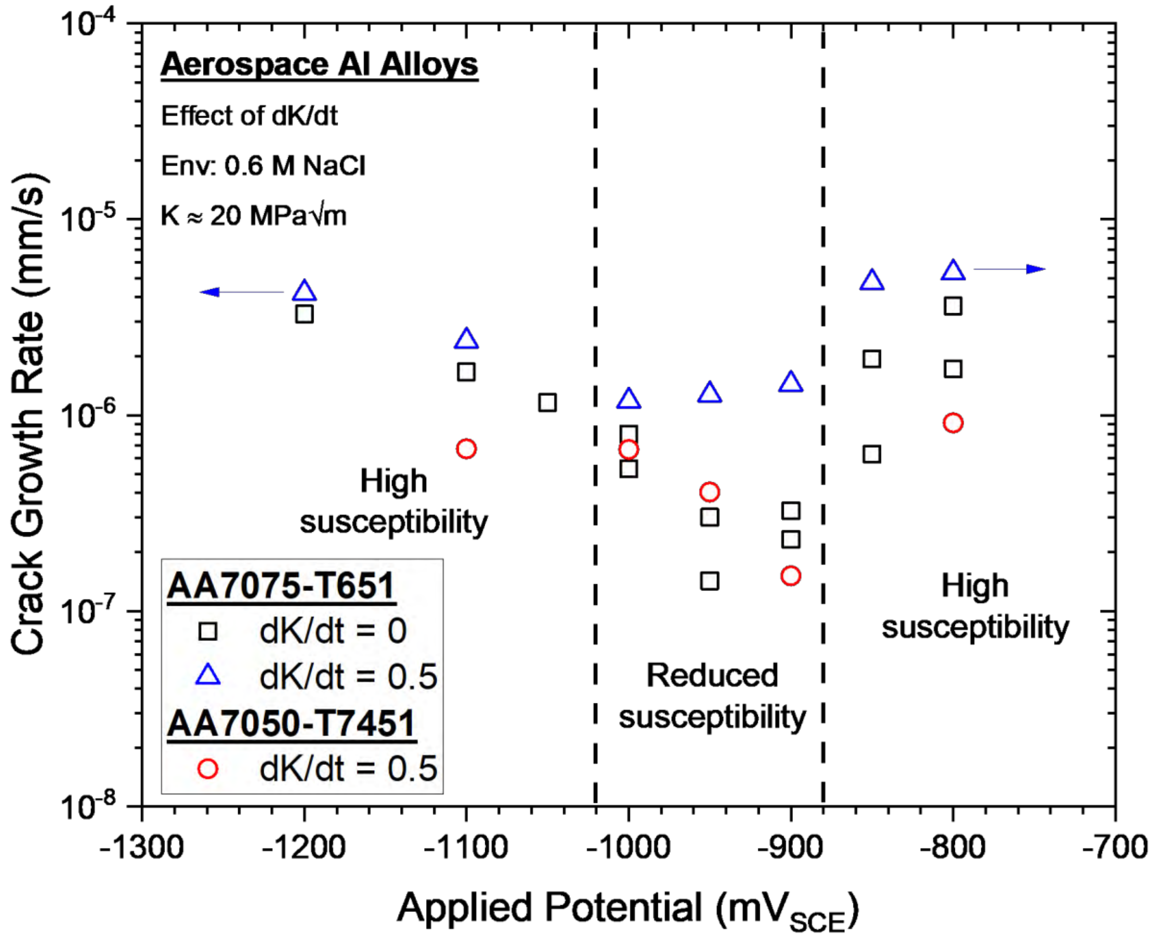


HEAC Analysis Paradigm
Ritchie-Thompson type damage model for strain-controlled crack

This paradigm can guide mechanistic understanding of the experimental observations…

Strain must exceed material resistance over X_{crit} for crack advance

Question: ***What governs the potential dependence of the HEAC behavior?***



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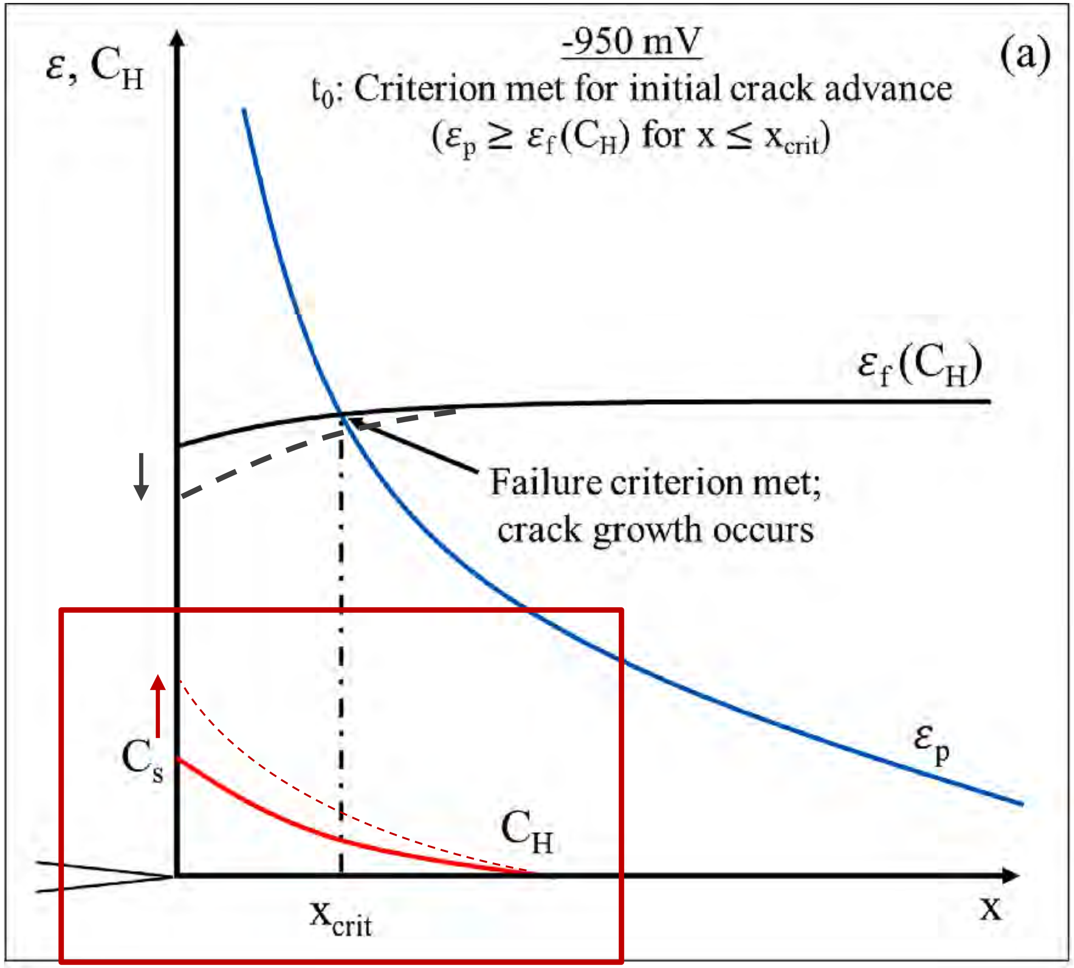


Hypothesis:
This is due to a modification of the surface H content

This will be governed by the over-potential for H production at the crack tip

That overpotential will vary with applied polarization

Question: ***What governs the potential dependence of the HEAC behavior?***

Experiments to quantify the extent of H generation as a function of potential (Scully)

Potentiostatic Polarization of Bare AA7075-T651 →

-700mV	-750mV	-800mV	-900mV	-1000mV	-1100mV	-1200mV	-1300mV	-1400mV	-1500mV	-1600mV
A	OC	C	C	C	C	C	C	C	C	C

Record Current vs time data →

Apply: $E(V\ vs\ SCE)$

Material response: $I(t)$ ↓ *Measure Gas evolution*

Experimental Variable: $t = 6\ hours$, $A = 0.785 cm^2$

Calculate: $Q = \int_{t_i}^{t_f} I(t)dt$

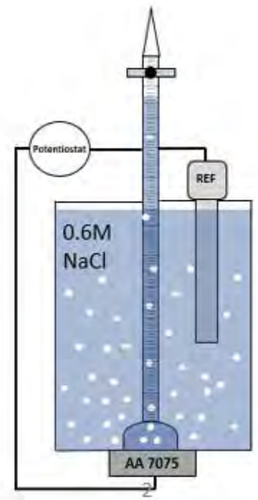
Plot Current/Charge vs time and Evolution rate of Hydrogen gas →

Plot: I(E) vs t

Plot: $Q(t) vs\ cycle$

Plot: Combined I(E) vs E & Hydrogen Evolution rate

Characterize → Hirox Digital Optical Microscope

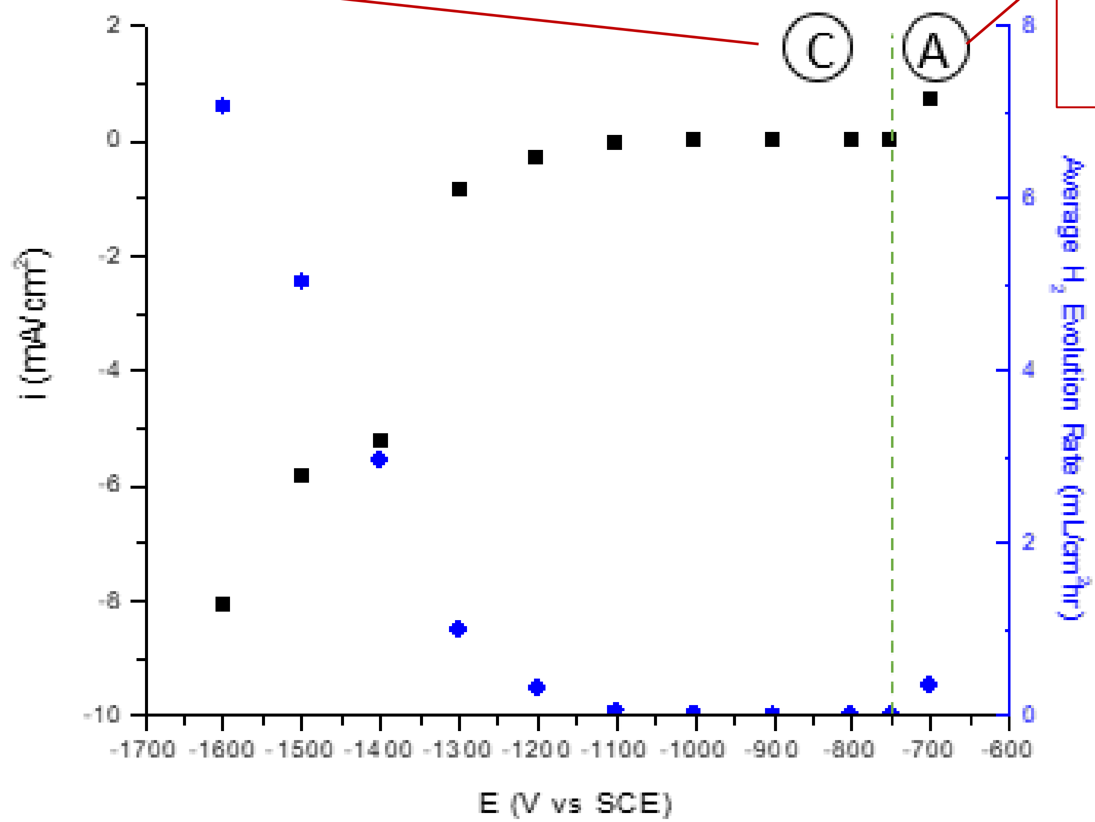


Question: What governs the potential dependence of the HEAC behavior?

Cathodic H Generation

7075-T651

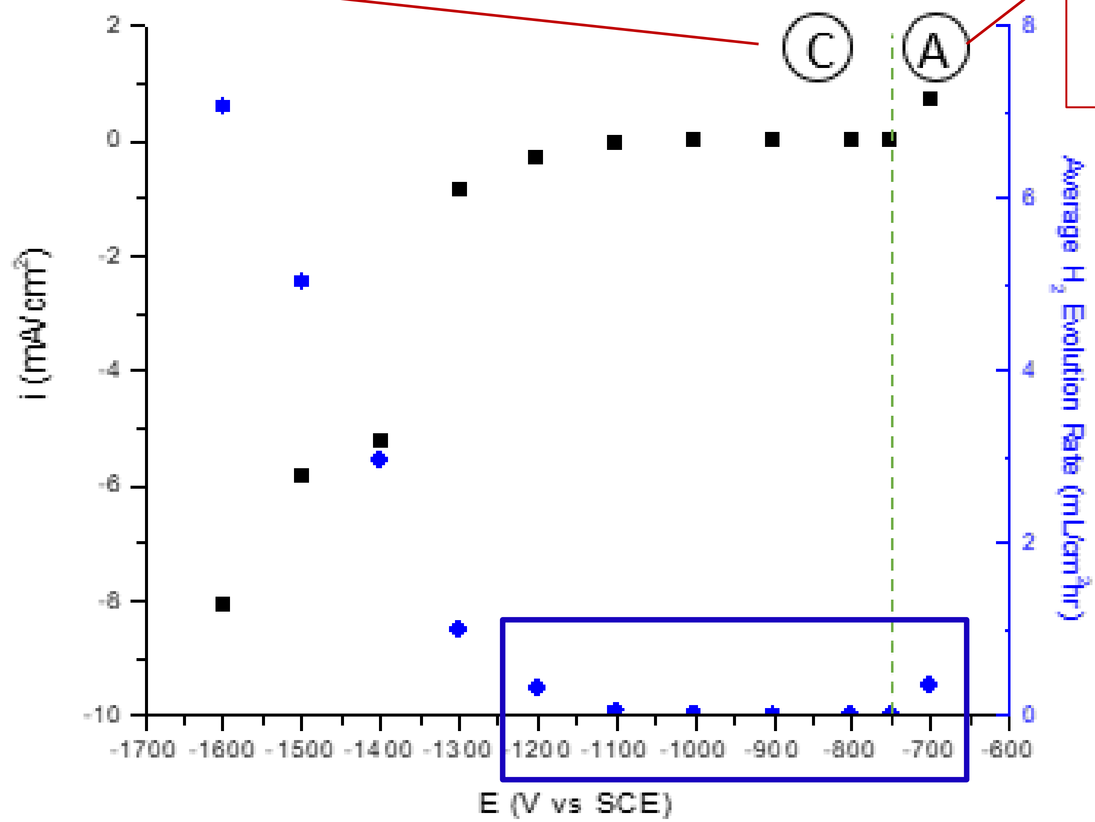
H Generation from local anodic dissolution and low pH crack tip environment



Question:* *What governs the potential dependence of the HEAC behavior?

7075-T651

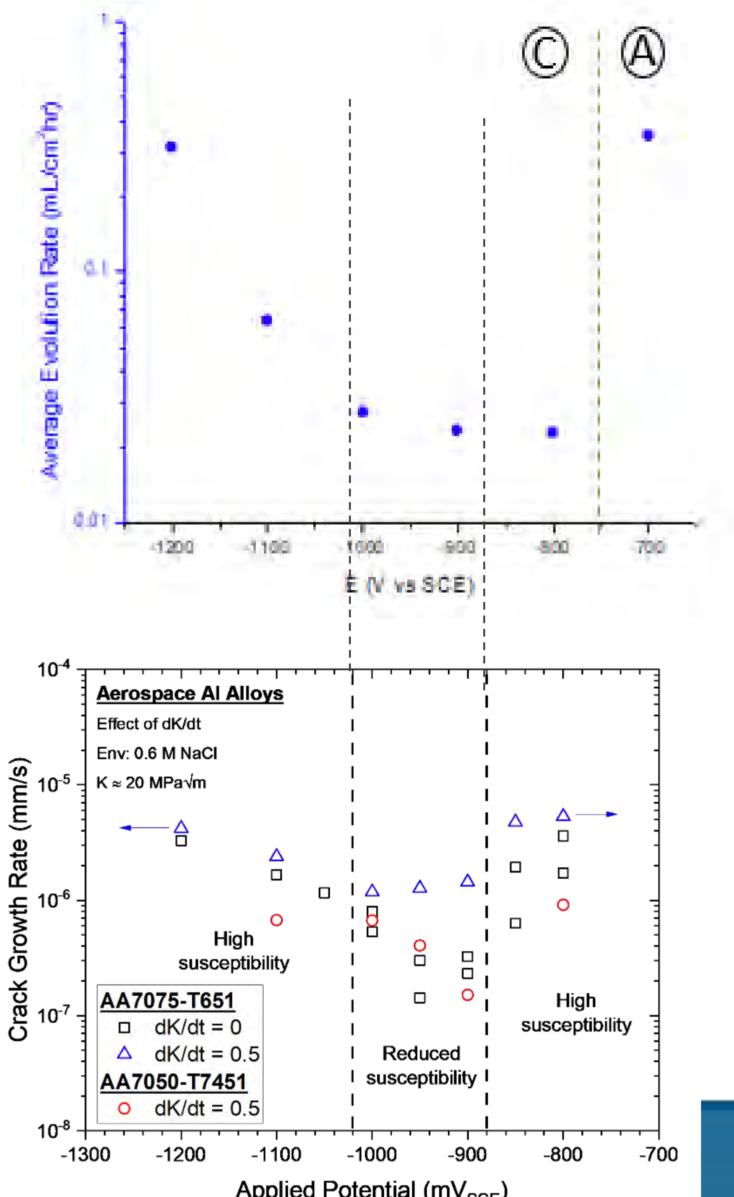
Cathodic H Generation



H Generation from local anodic dissolution and low pH crack tip environment

Blow up this region and compare to HEAC kinetics

Question: What governs the potential dependence of the HEAC behavior?

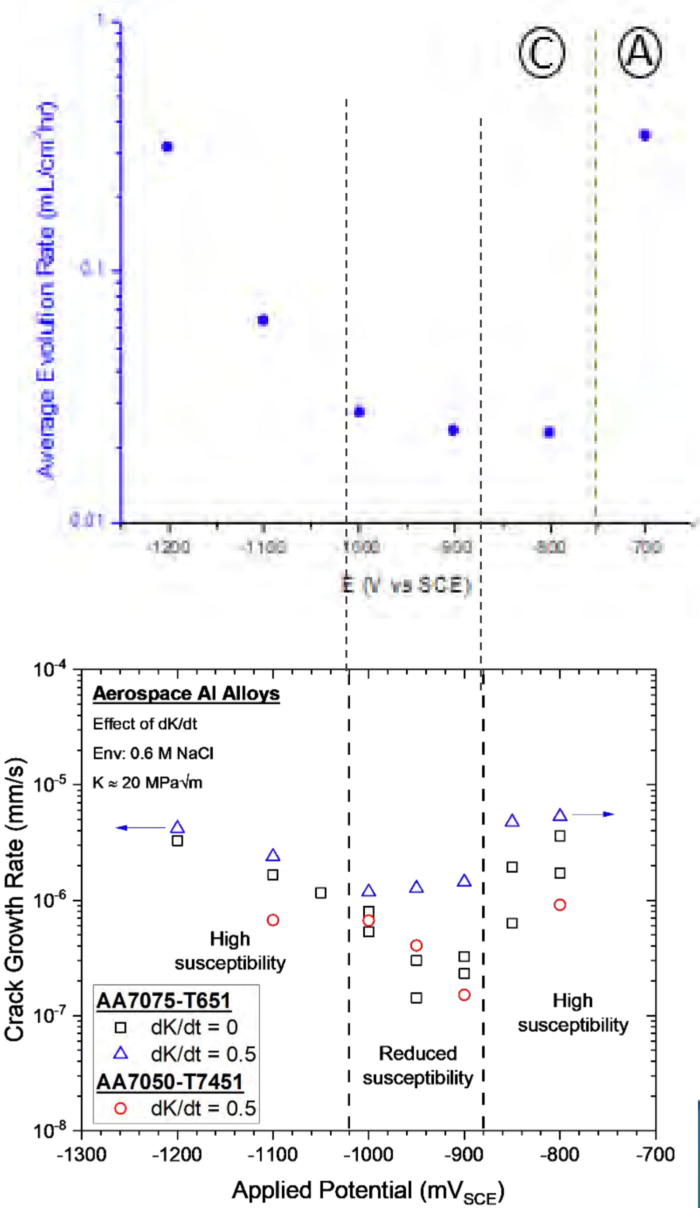


7075-T651

Critical Observation:

- *Potentials with reduced HEAC susceptibility corresponds with the reduced levels of H generation*

Question: What governs the potential dependence of the HEAC behavior?



7075-T651

Critical Observation:

- ***Potentials with reduced HEAC susceptibility corresponds with the reduced levels of H generation***

Challenges:

- *H_2 gas collection only a proxy for H-uptake*
- *H generation experiments not performed in crack tip solution*
  - *Sensitivity was analyzed*
  - *Sensitive at cathodic E where it goes alkaline*
- *H generation at anodic potentials (localized) versus more global for cathodic*

Talk Objectives:

- ***Systematically characterize the EAC behavior of 7075-T651 and 7050-T7451 alloys as a function of applied potential***
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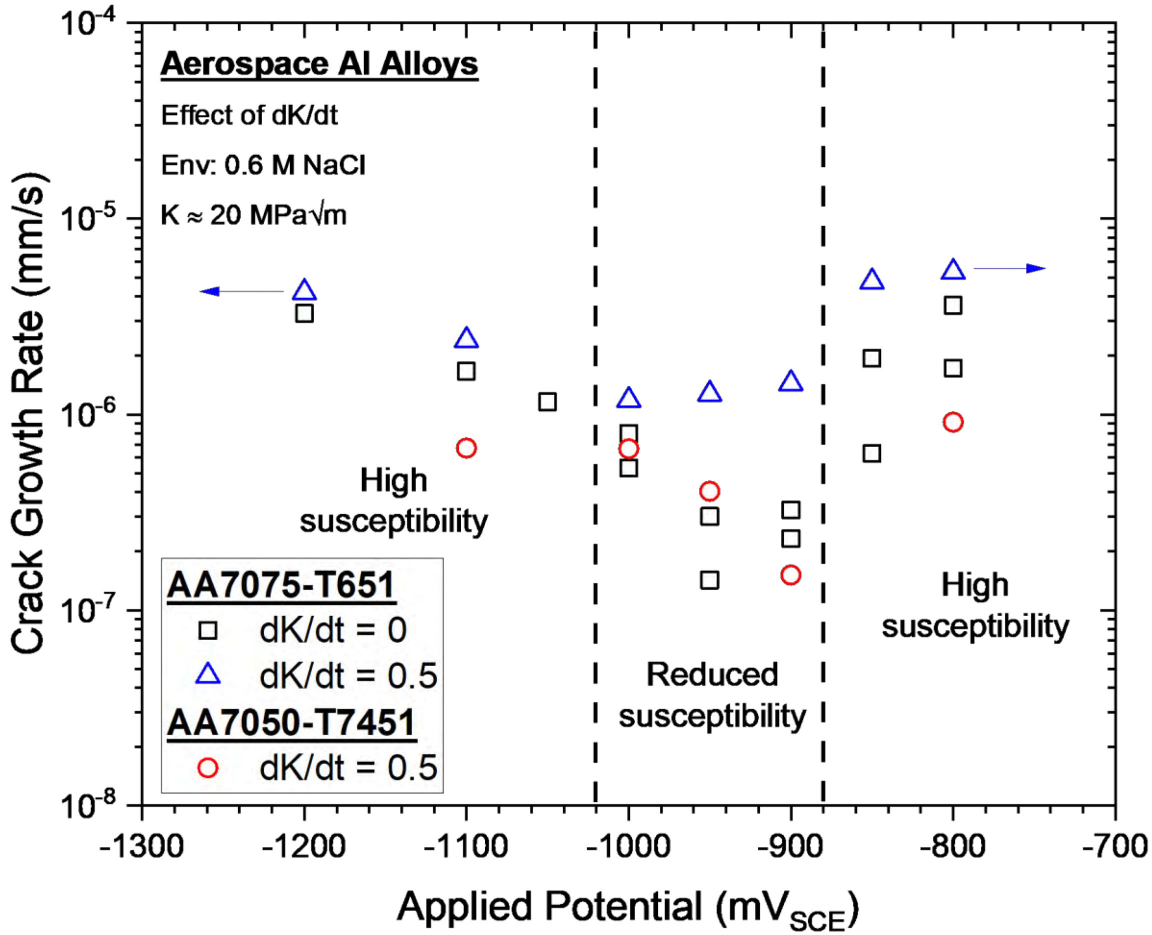
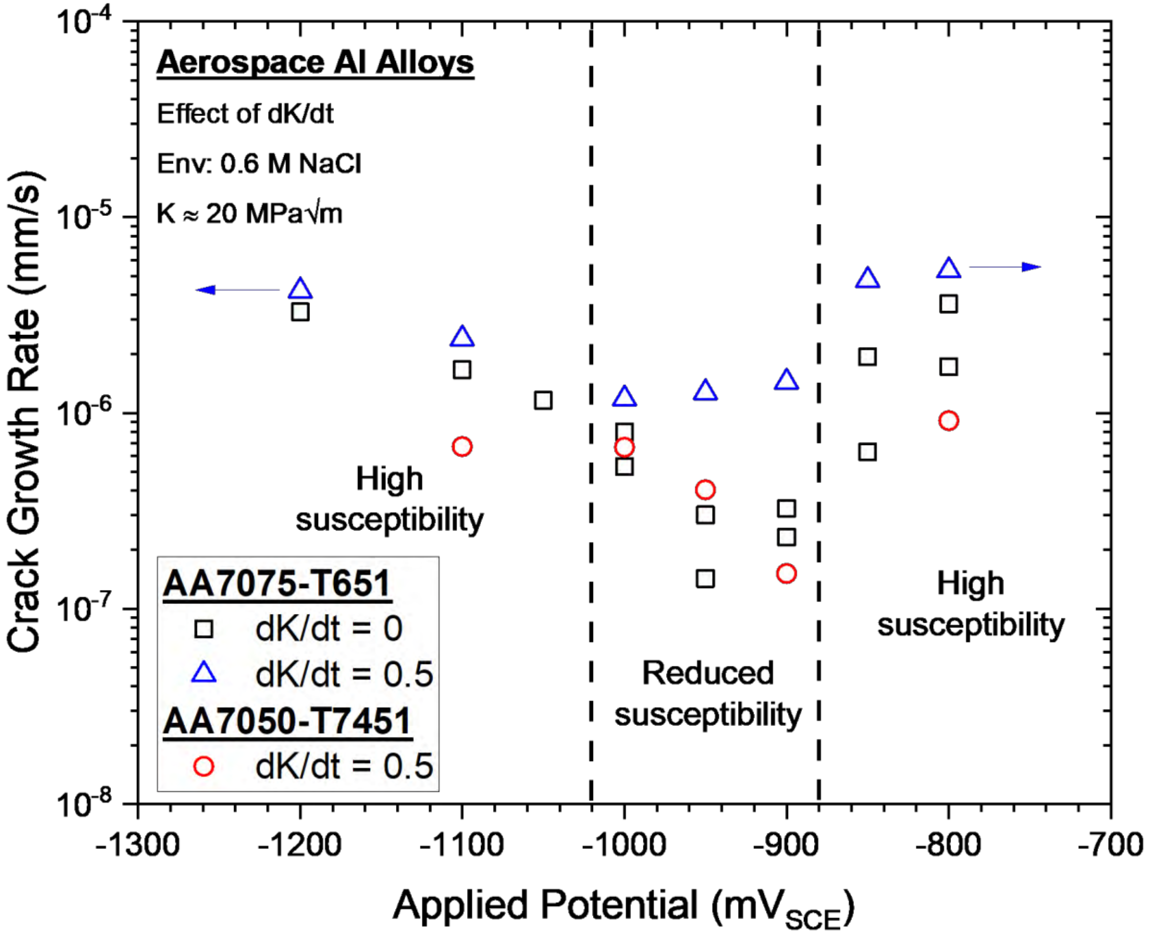
Question: Why is 7050-T7451 (High Cu, OA) less susceptible than 7075-T651



Question: Why is 7050-T7451 (High Cu, OA) less susceptible than 7075-T651

Does the higher Cu content lead to less dissolution, thus a less aggressive chemistry, thus lower H values??



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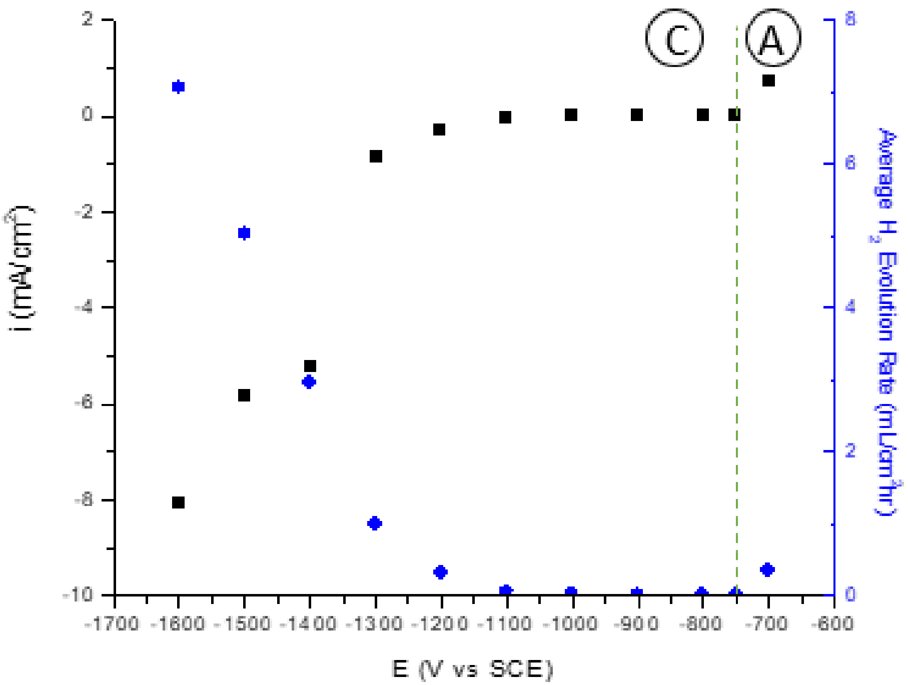
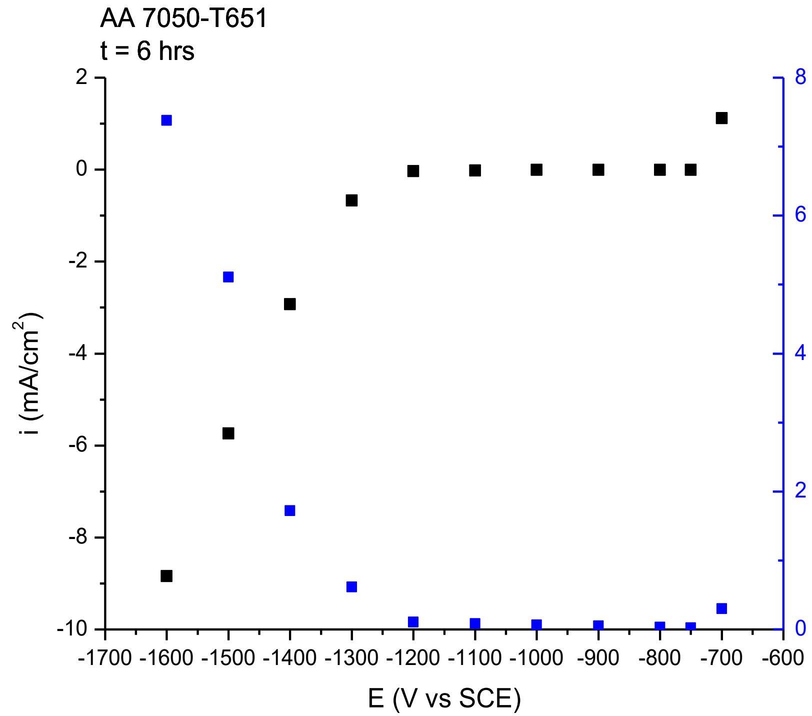


7075-T651



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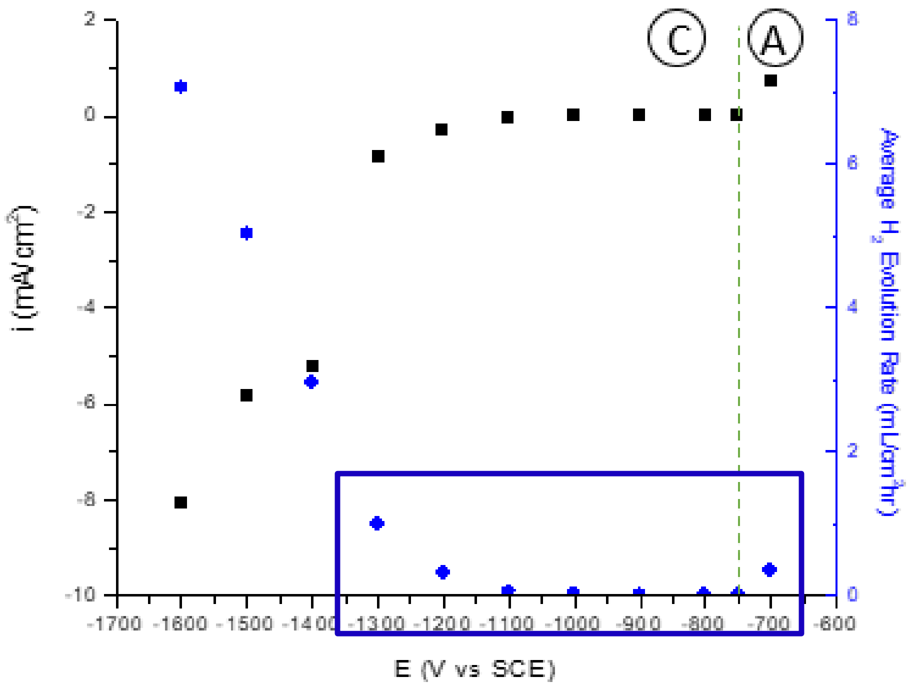
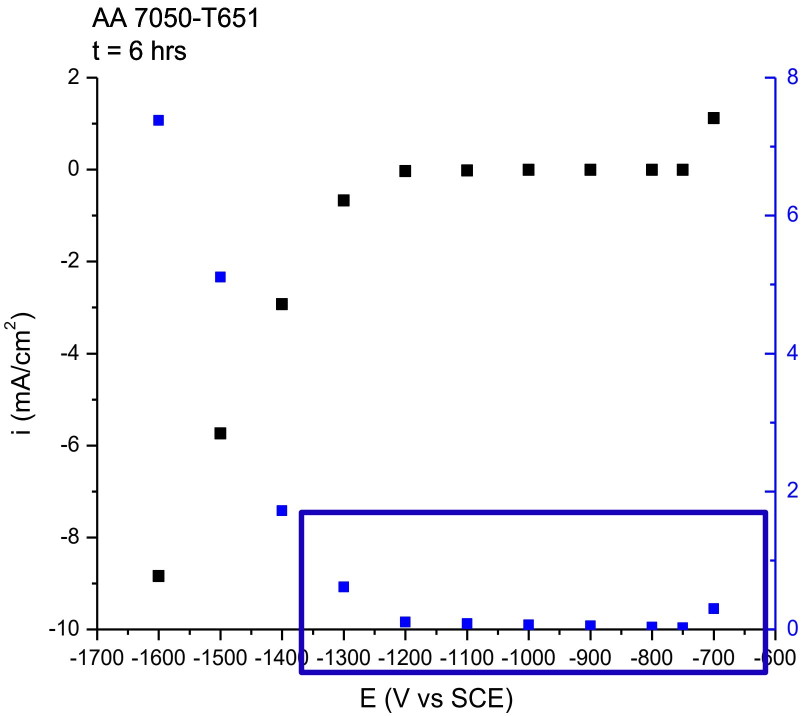


7075-T651



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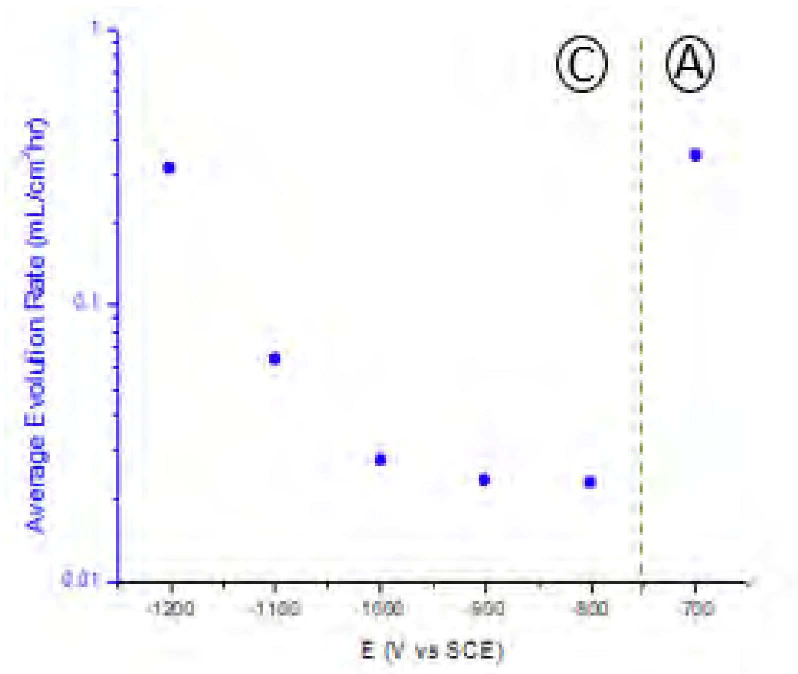
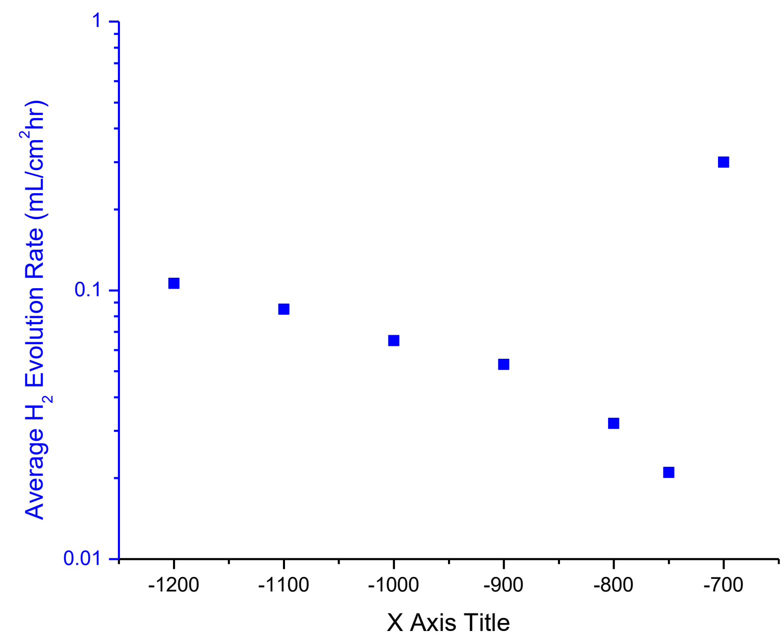
Closer examinations suggests that 7050-T7451 actually has modestly higher H generation at cathodic potentials in the transition regime



7075-T651



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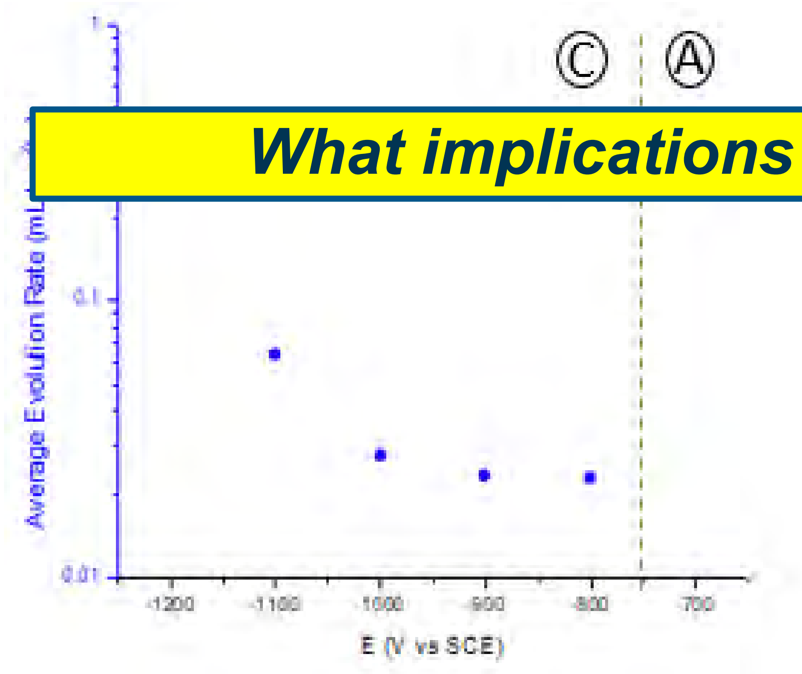
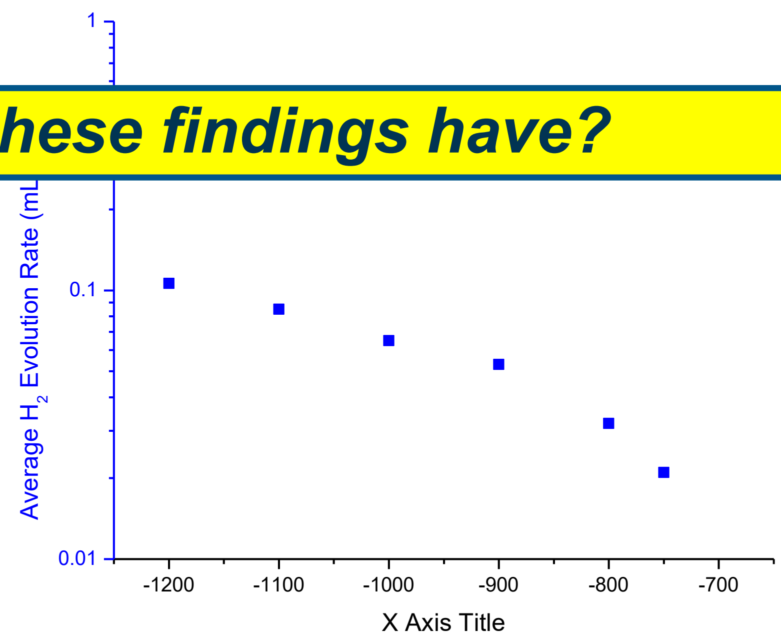
What implications do these findings have?

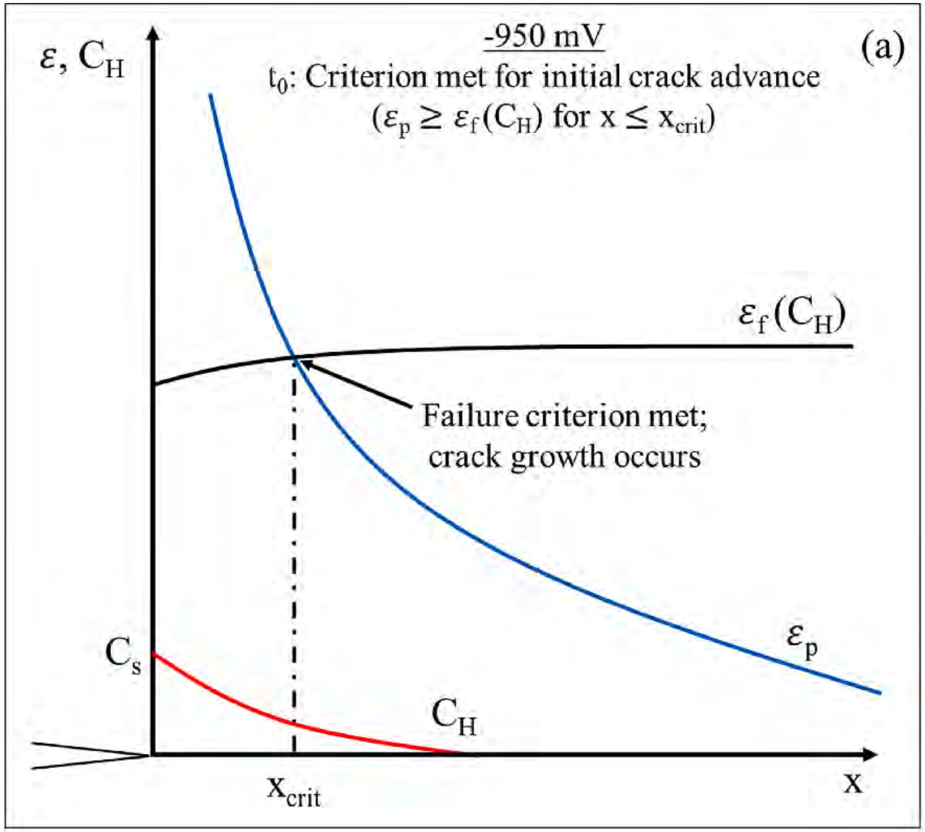


7075-T651



7050-T7451

Mechanistic Implications



If Cu and OA is not impacting the chemistry that governs the surface H concentration (e.g C_S)…

This then supports a governing role of:

- ***Intrinsic material response***
  - *Impact of slip morphology*
  - *Impact of H diffusion*
  - *H redistribution*
  - *Intrinsic failure criteria*
    - *Local defects*
    - *Solute segregation*
  - *Sensitivity to the failure criteria to a given amount of H*

Questions

Understanding Performance of New Generation 7xxx Aluminium Alloys

Prof Joseph Robson

joseph.robson@manchester.ac.uk

DSTL/RAEng Chair in Alloys for Extreme Environments

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The University of Manchester

About Me

- Professor of Physical Metallurgy, University of Manchester UK
- DSTL/RAEng Chair in Alloys for Extreme Environments (2021-2026)
- Working on:
  - Metal fragmentation simulation and measurement
  - Modelling metal/laser interactions
  - Additive manufacture of Al alloys
  - EAC performance of new generation 7xxx Al
- Background
  - PhD in steel metallurgy (1996)
  - Industrial research fellow (British Aluminium/Alcoa) (1999-2003)
  - Academic in light alloy research group (2003-now)

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EAC of New Gen 7xxx Alloys

- Major project at UoM (2017-2024) focused on understanding EAC performance of new gen 7xxx alloys for civil aerospace
  - Testing methods and crack growth measurements
  - Nano-scale microstructure studies
  - X-ray tomography studies of crack morphology
  - In-situ studies of crack initiation and growth
  - Modelling and simulation of initiation and growth

Phil Prangnell
Academic lead

Tim Burnett
Testing and tomography

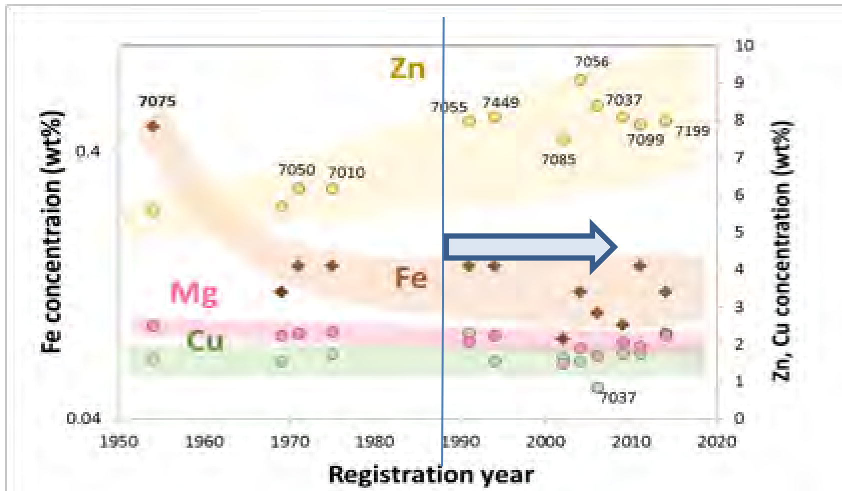
Chris Race
Atomistic simulation

Pratheek Shanthraj
Phase field and crystal plasticity modelling

Henry Holroyd
Consultant

- Now taking this understanding to apply to defence conditions and platforms (collaboration with UK DSTL and 1710 Naval Air Squadron)

Development of 7xxx Thick Plate Aerospace Products



- o Thicker plate products (100 -280 mm) – for machining integral components
- o Higher strength and/ or same strength as 7050-T7651 with……
  - o Lower quench sensitivity
  - o Higher or equivalent damage tolerance – corrosion performance

e.g. alloys like 7085

- Increased Zn
- Move Mg/Zn from excess to deficient - relative to $MgZn_2$

e.g. Alloys like 7449, 7055

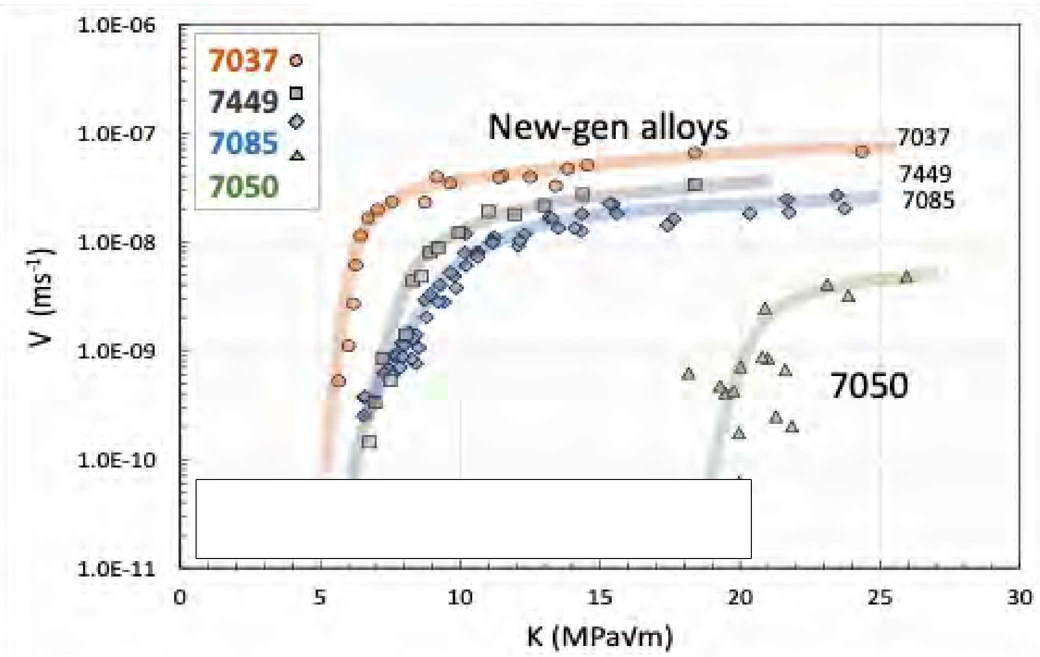
- Increased Zn but maintain balance relative to $MgZn_2$

→ Lower quench sensitivity → Reduced constituents – Al_7Cu_2Fe, No S, or Mg_2Si → Higher η' V_f → higher strength

The University of Manchester

EAC in Humid Air (T76)

New gen 7xxx pass industry standard SCC testing (ASTM-G47) in saline solutions but…



Environment
70° C with 85% RHA

Alloy	K_{1HEAC} MPa√m	v_{II} $m\ s^{-1}$
AA7050	17-20	3×10^{-9}
AA7449	6-7	3×10^{-8}
AA7085	6-7	2.1×10^{-8}
AA7037	5-6	6.6×10^{-8}

v_{II} => 6 – 20 times 7050

K_{1HEAC} => < half 7050

Corrosion Science

journal homepage: www.elsevier.com/locate/corsci

Environmental cracking performance of new generation thick plate 7000-T7x series alloys in humid air

Elisabeth Schwarzenböck, Eric Ollivier, Alistair Garner, Alex Cassell, Theo Hack, Zak Barrett, Christian Engel, Tim L. Burnett, N.J. Henry Holroyd, Joseph D. Robson, Phil B. Prangnell

Corrosion Science 171 (2020) 108701

EASA
European Aviation Safety Agency

Safety Information Bulletin
Airworthiness
SIB No.: 2018-04R1
Issued: 13 September 2018
Subject: Environmentally Assisted Cracking in certain Aluminium Alloys

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Experimental Techniques and Facilities

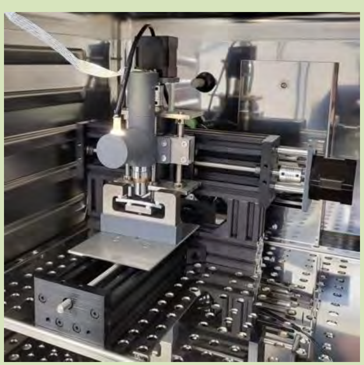
Testing

Static load test

Constant displacement DCB test

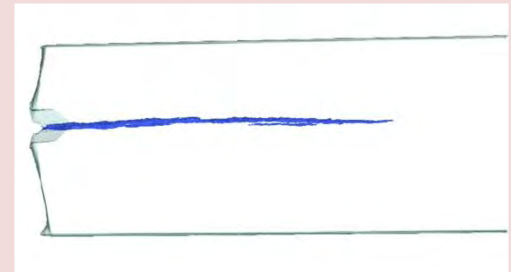
Slow strain rate test

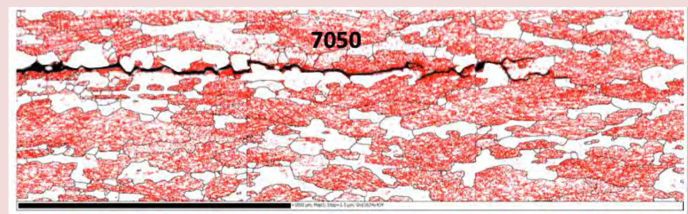
In-situ 4-point bending



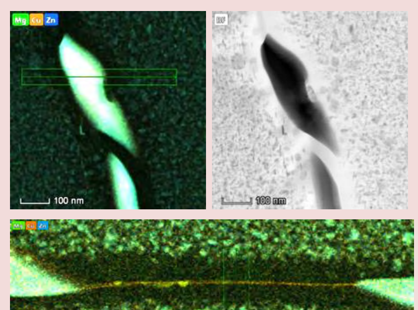
Characterization

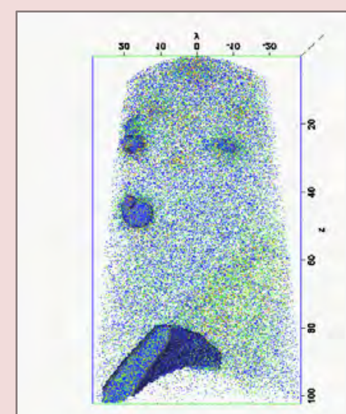
X-ray tomography: True crack path, branching and crack morphology





Site selected EBSD: effect of Grain structure





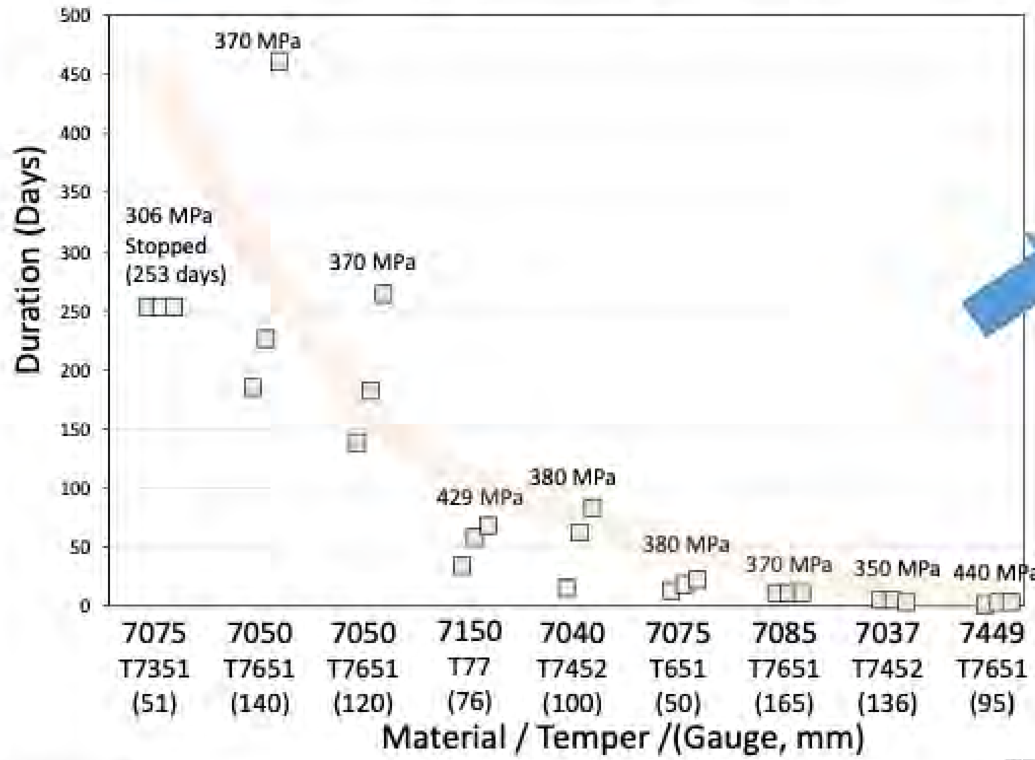
TITAN ChemiSTEM + atom probe: atomic scale composition

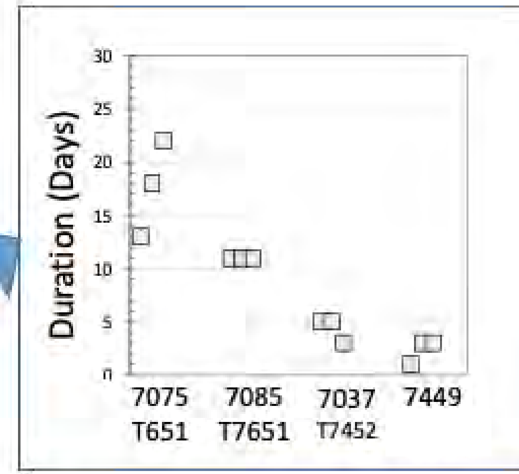
Static Load Tests - Lifetime

The University of Manchester

All alloys compared at 85 % Yield (0.2% Proof)

3 tests for each condition





Duration reduced from ~ 1 year to < 2 weeks

Environment
70° C with 85% RHA


Corrosion Science

journal homepage: www.elsevier.com/locate/corsci

Environmental cracking performance of new generation thick plate 7000-T7x series alloys in humid air

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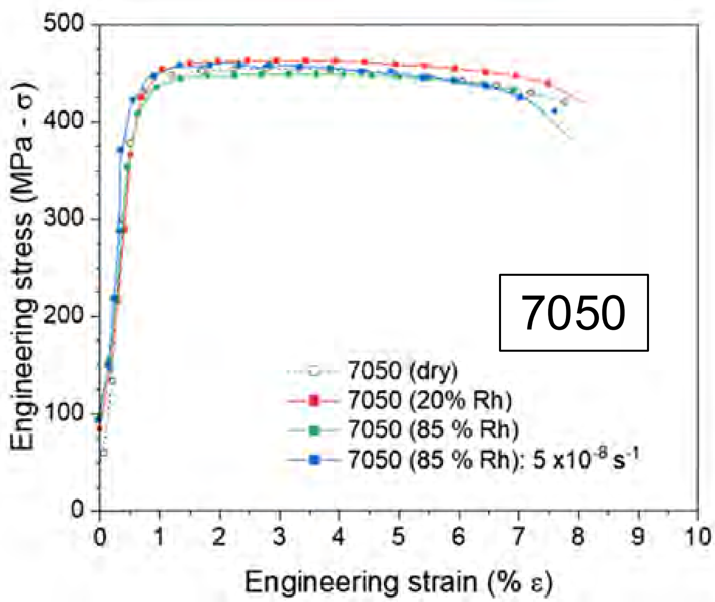
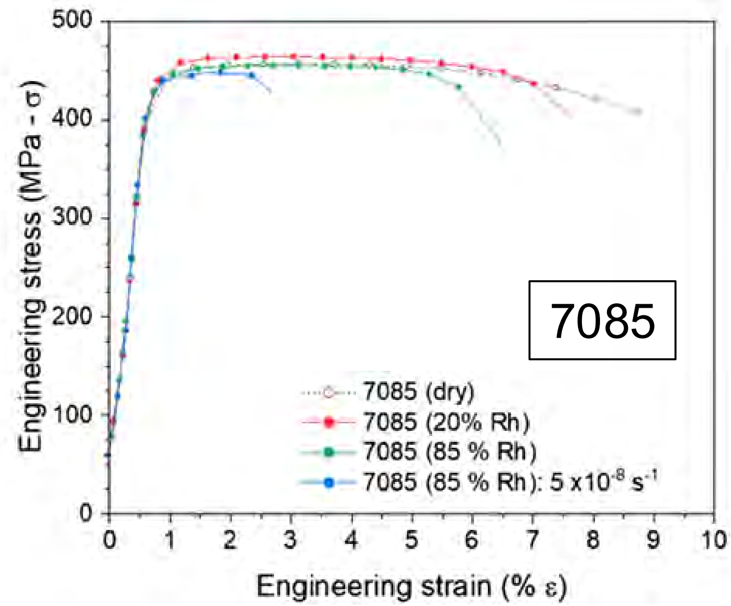
Influence of Humidity (SSRT)

- Slow strain rate tests at different humidity levels
- SR = 8 x 10^{-7} and 5 x $10^{-8} s^{-1}$, T = $70^{o}C$





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Understanding the environmentally assisted cracking (EAC) initiation and propagation of new generation 7xxx alloys using slow strain rate testing

Y. Aboura [a], A.J. Garner [a], R. Euesden [a], Z. Barrett [b], C. Engel [c], N.J.H. Holroyd [a,d], P. B. Prangnell [a], T.L. Burnett [a,*]

[a] Department of Materials, The University of Manchester, M13 9PL, UK
[b] Airbus UK, Pegasus House, Aerospace Ave, Filton, Bristol BS34 7PA, UK
[c] Airbus, Airbus, Airbus Operations GmbH, Airbus-Allee 1, 28199 Bremen, Germany
[d] Department of Materials Science and Engineering, Case Western Reserve University, Cleveland, OH, USA

Corrosion Science, 199, 1 May 2022, 110161

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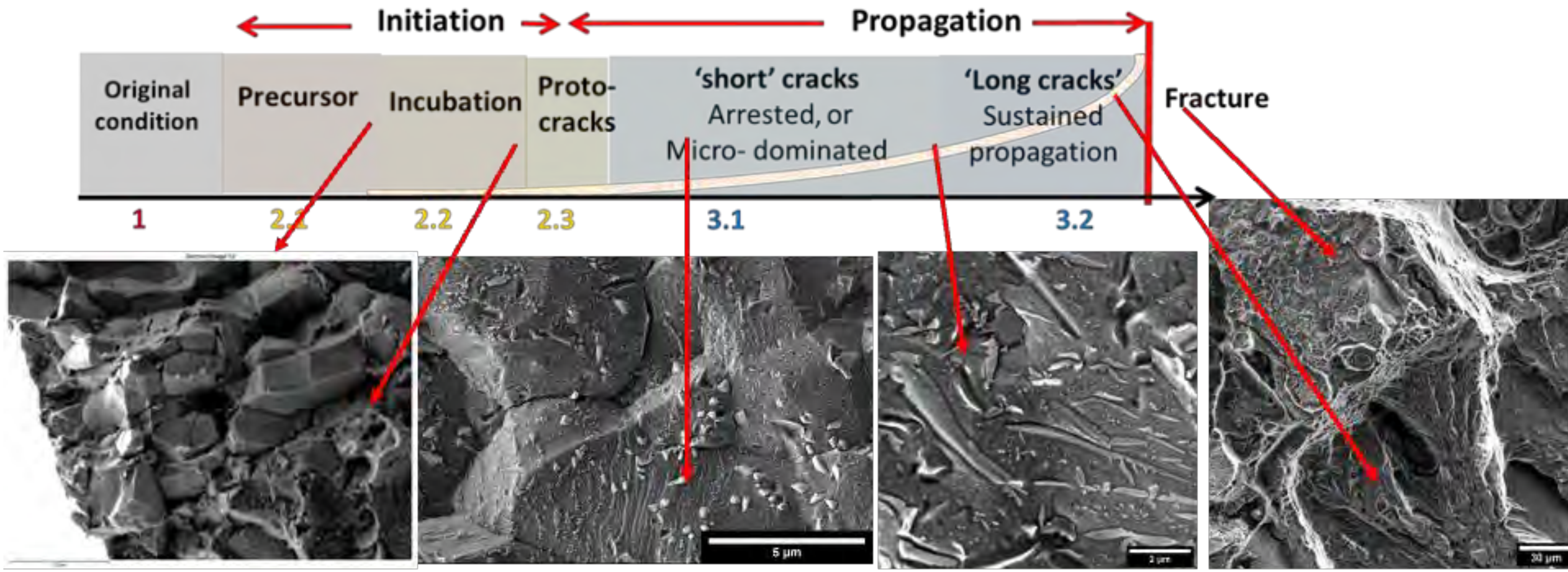
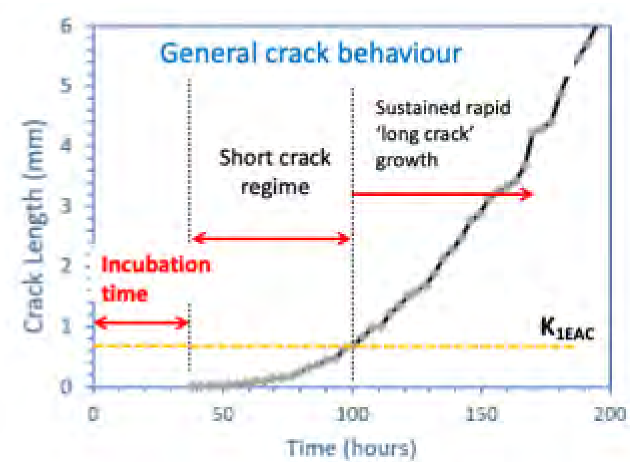
Sequence of Failure (SSRT)
7085-T7651

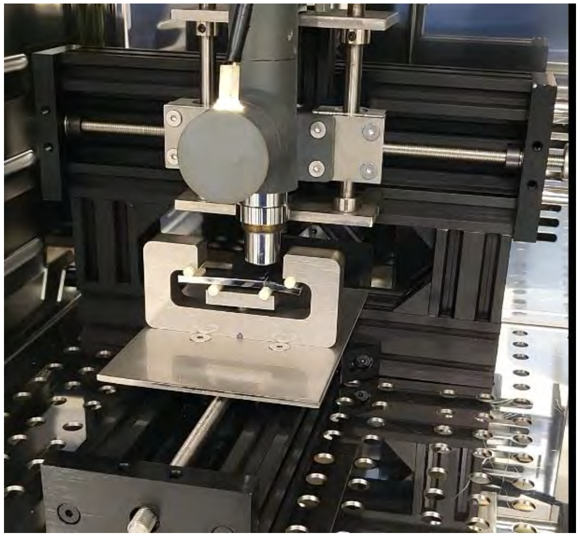


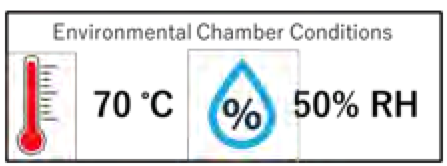
Sequence of EAC failure is now identified.
Consistent with observations from in-service failure.



Focus on understanding initiation stages and transition to sustained crack growth

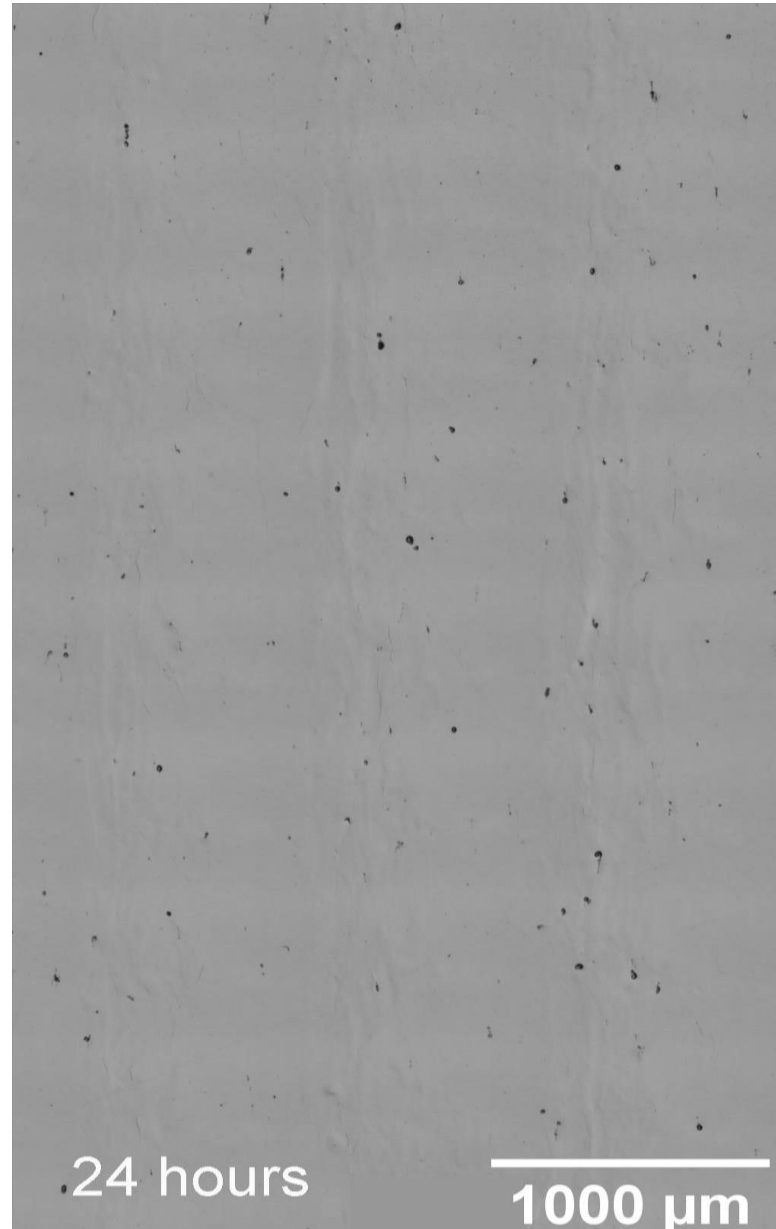
In-situ 4-point bend – Initiation 7085



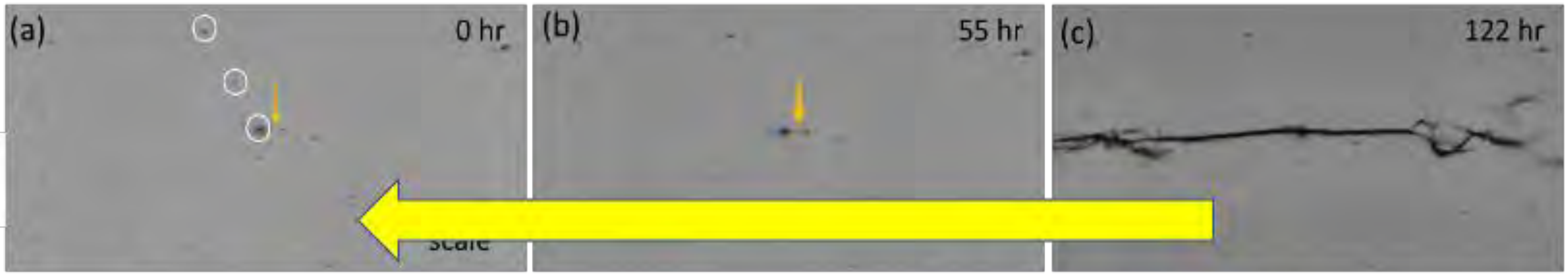


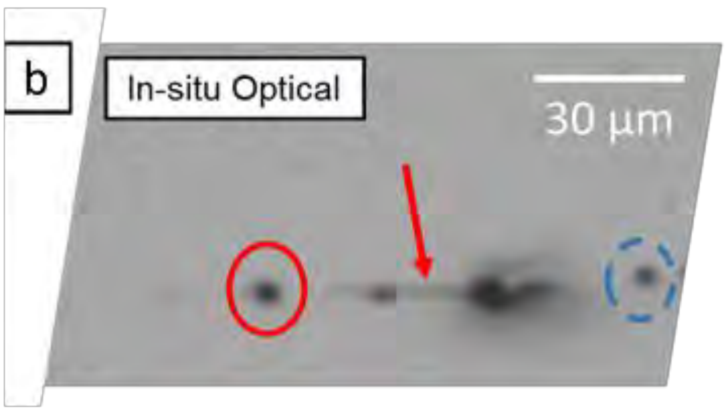
- Trace back crack to unambiguously determine initiation point

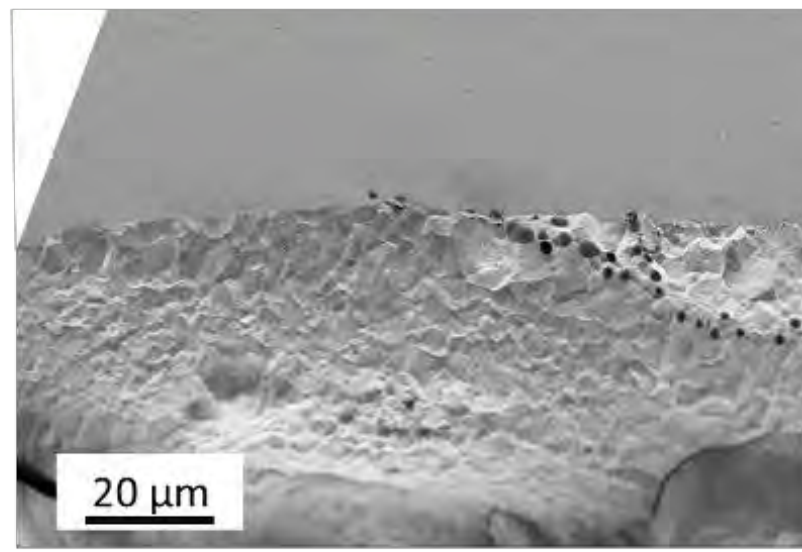
R. T. Euesden et al. Corrosion Science 216 (2023) 111051



7085 – Initiation Sites





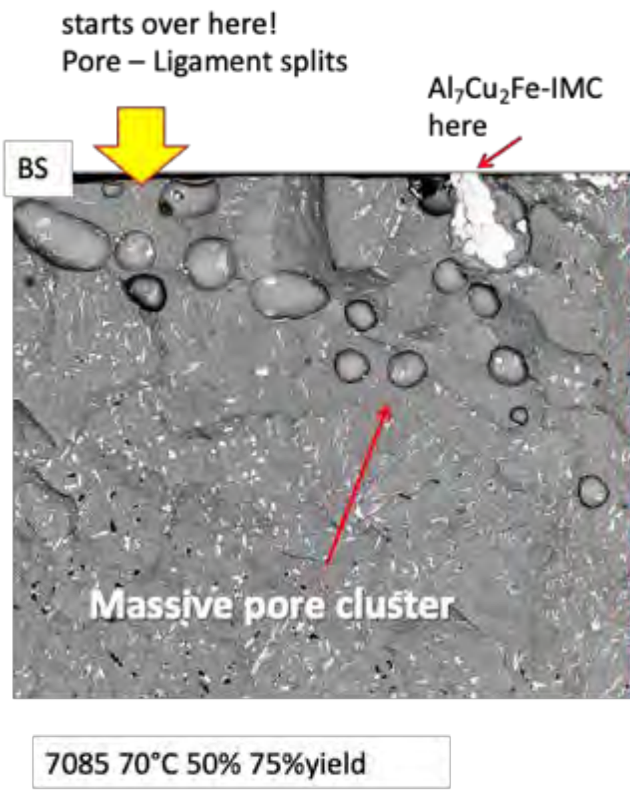


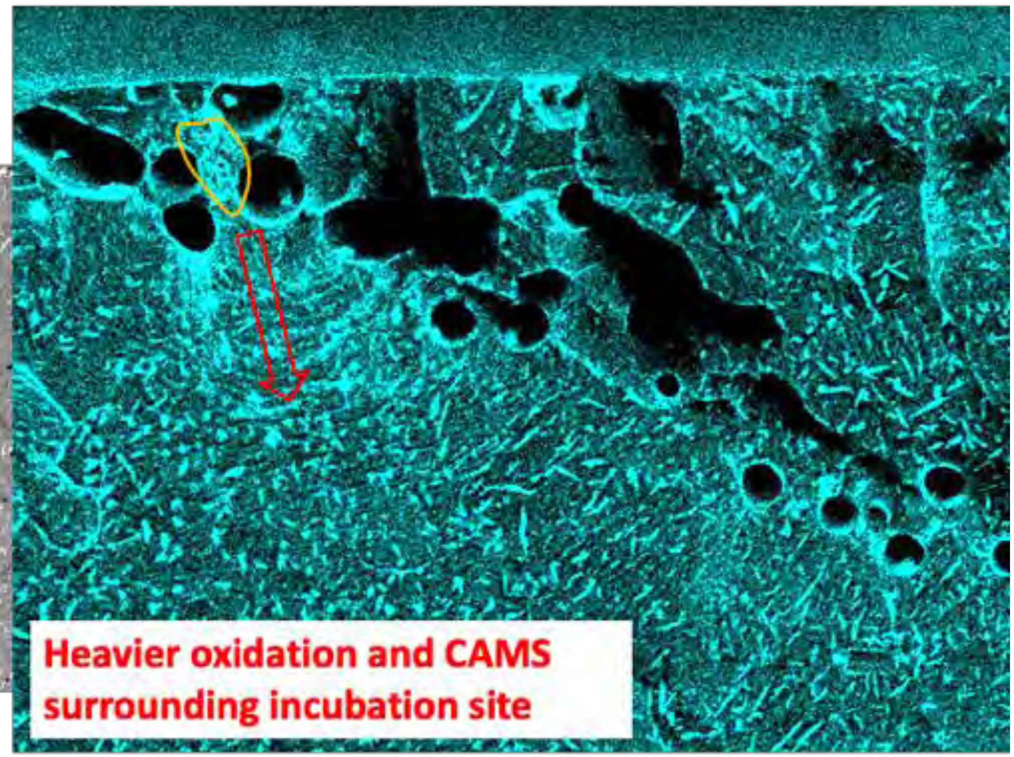
7085

7085 70°C 50% 75%yield

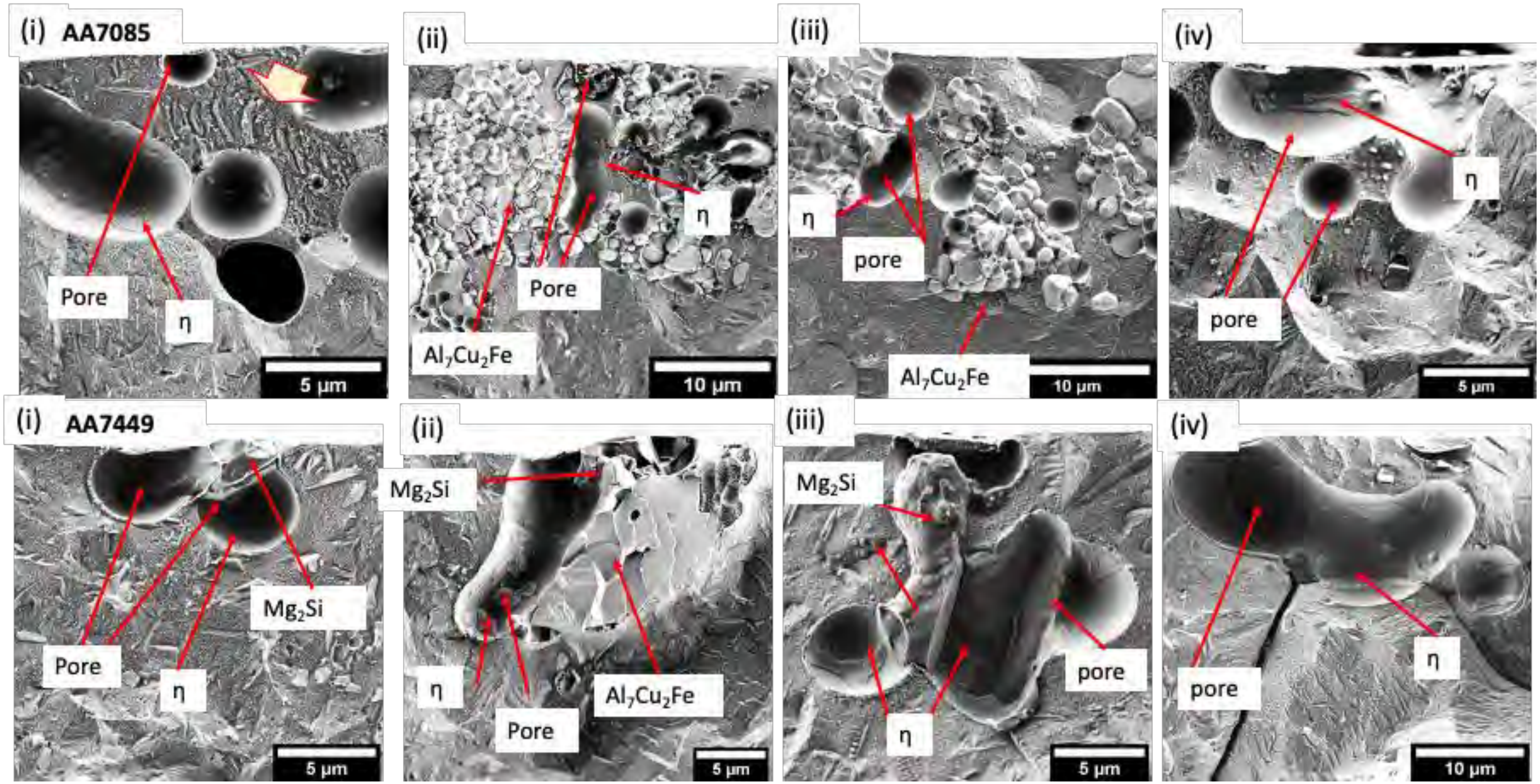
Initiation Site Detail

- Initiation always associated with pores/pore clusters
- Pores often correlated with intermetallic particles

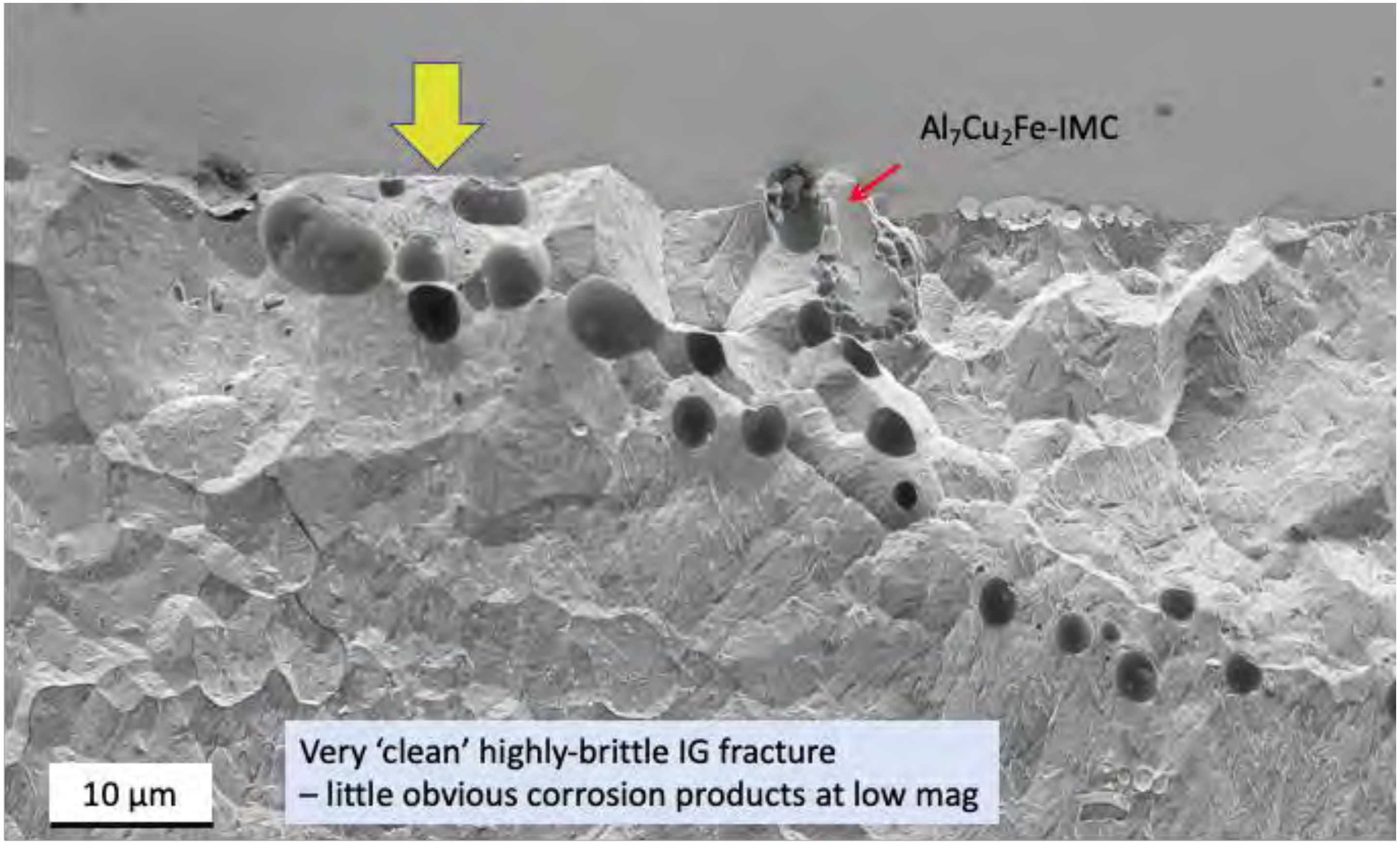




Examples of Initiation Sites



Typical Morphology – AA7085



7085 70°C 50% 75%yield

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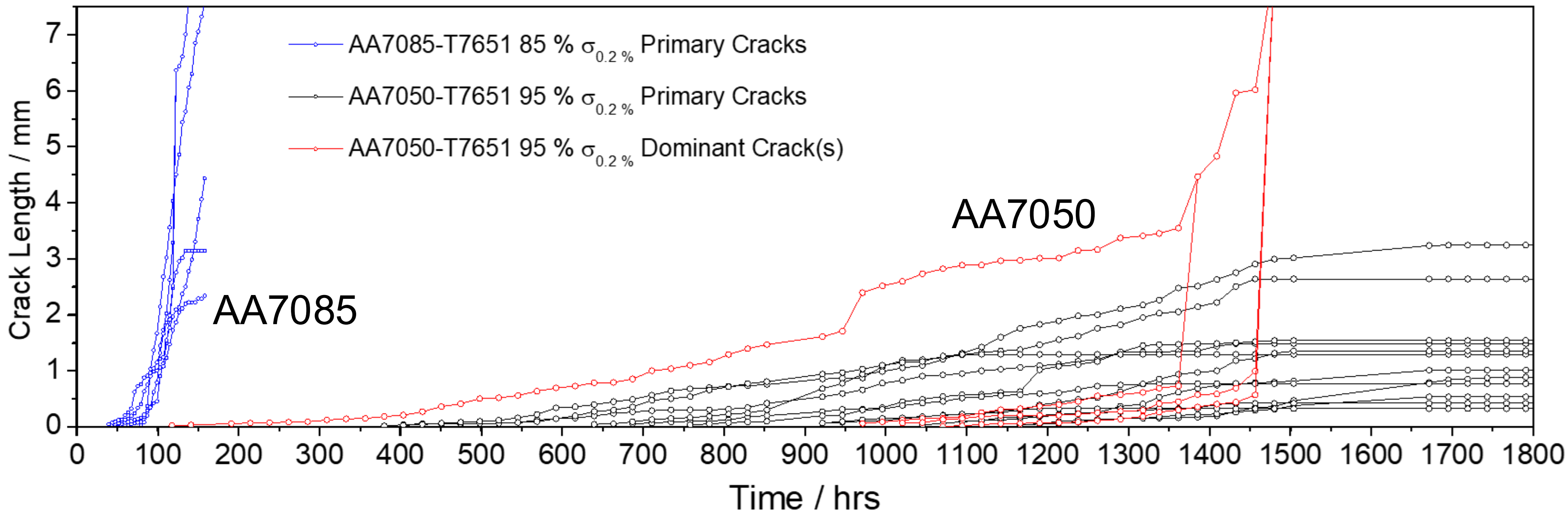
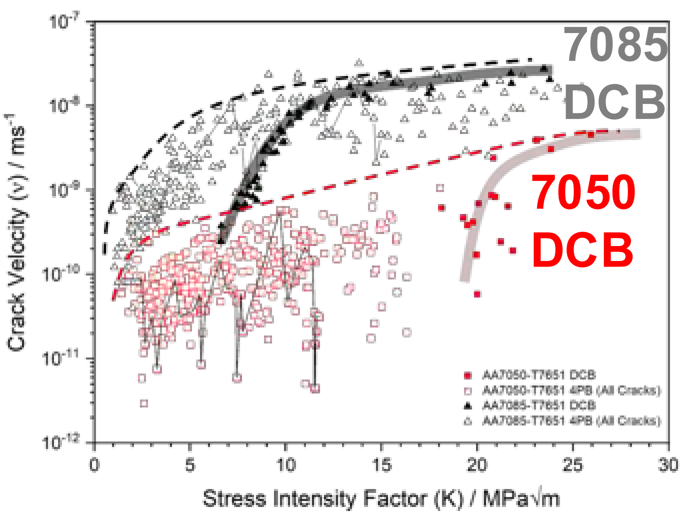
Crack Length Measurement

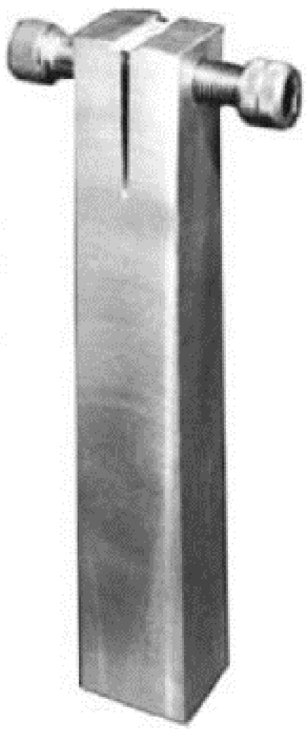


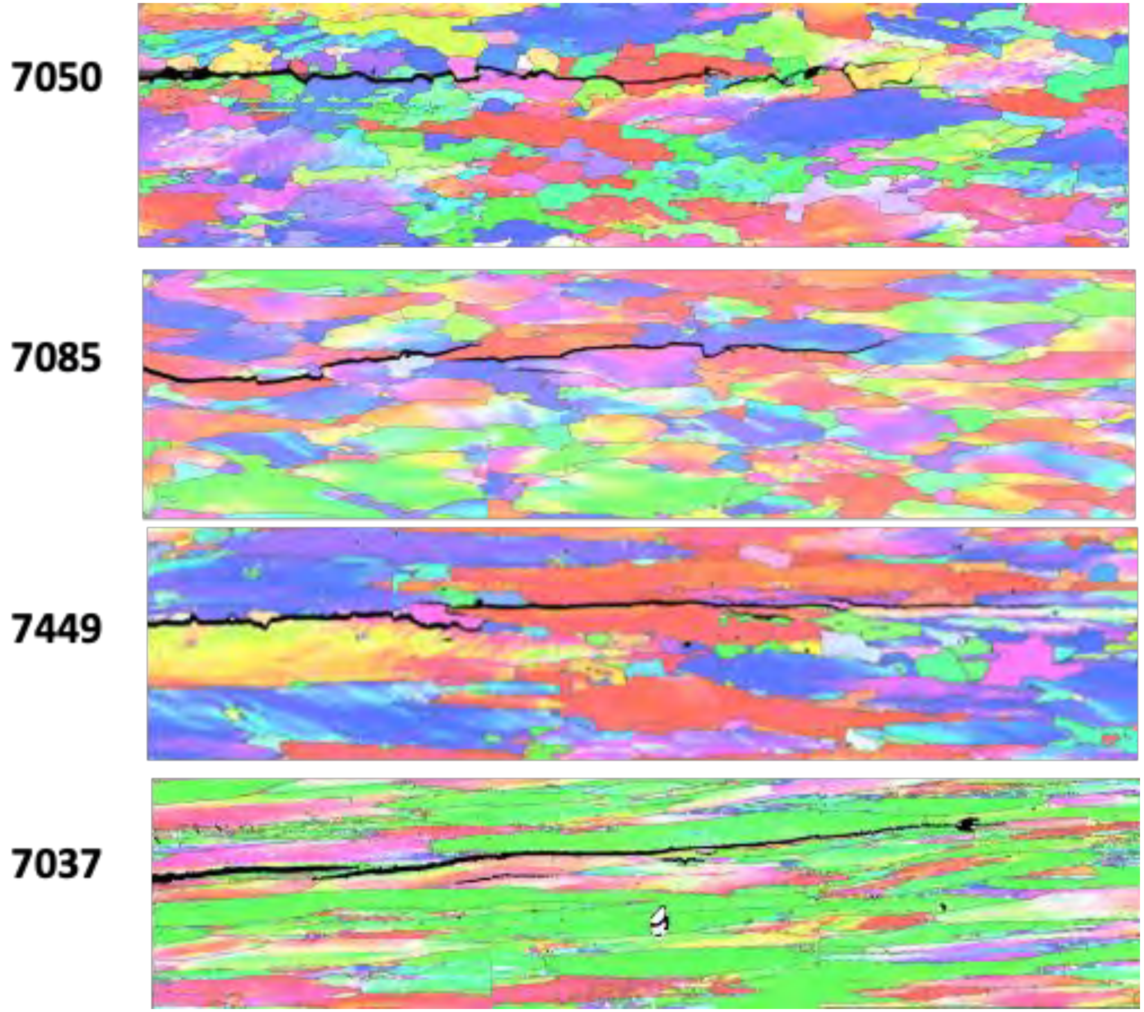


V-K curves measured from individual cracks

Cracks are growing at K<<K_{1EAC} determined from DCB test

Sustained Crack Growth (DCB): Crack Path





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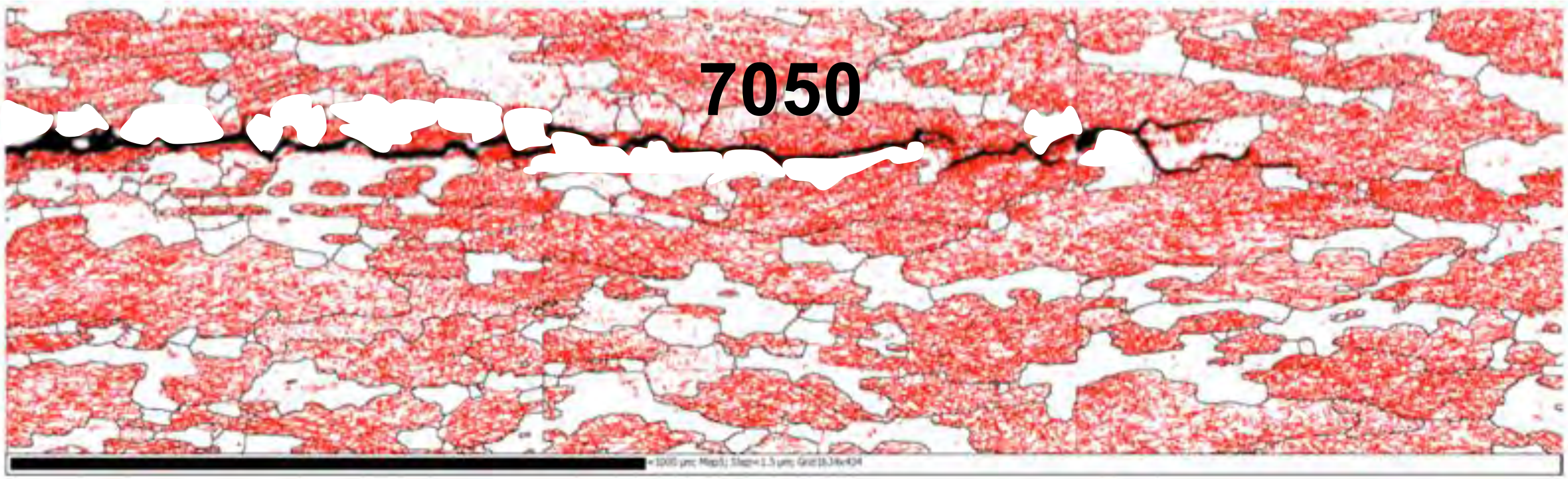
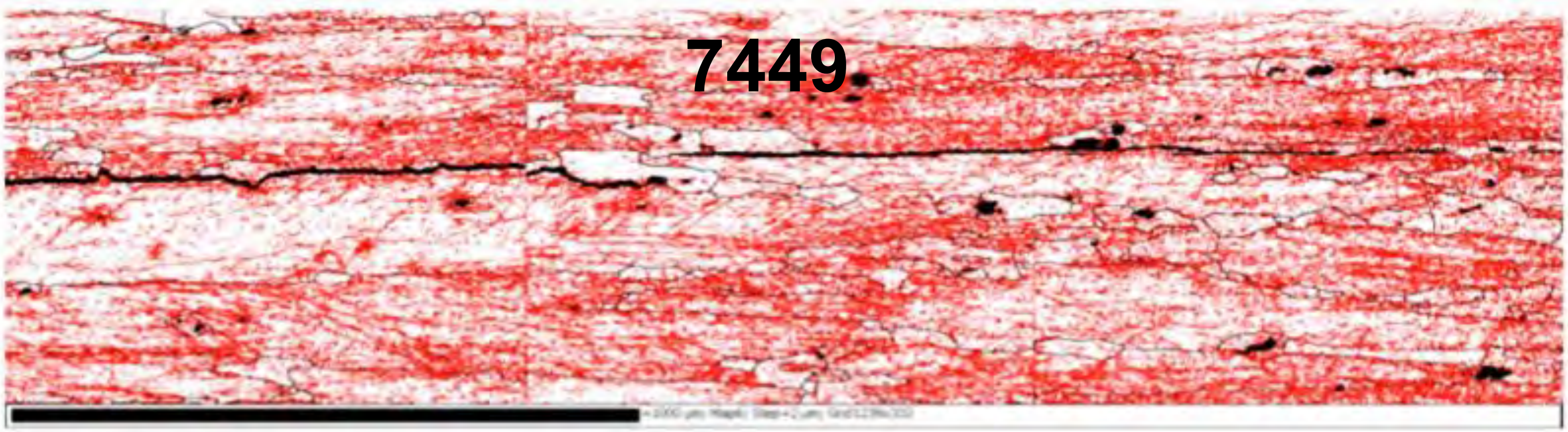
Effect of Recrystallized Grains





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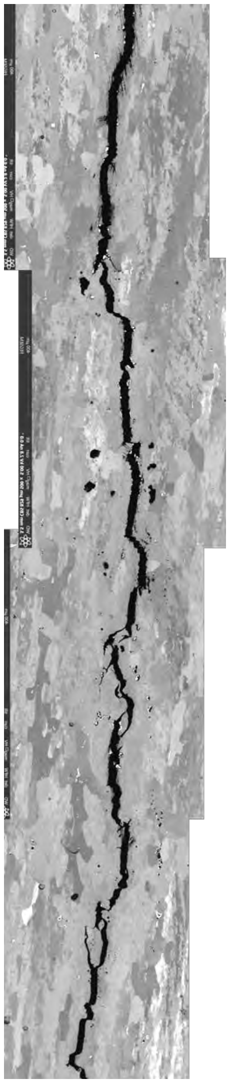
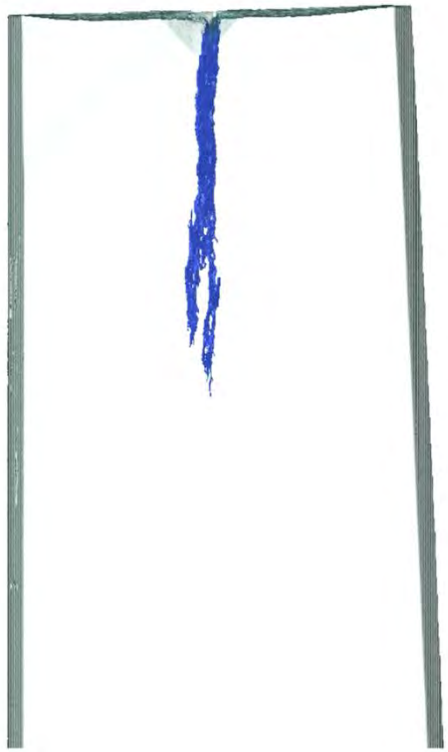
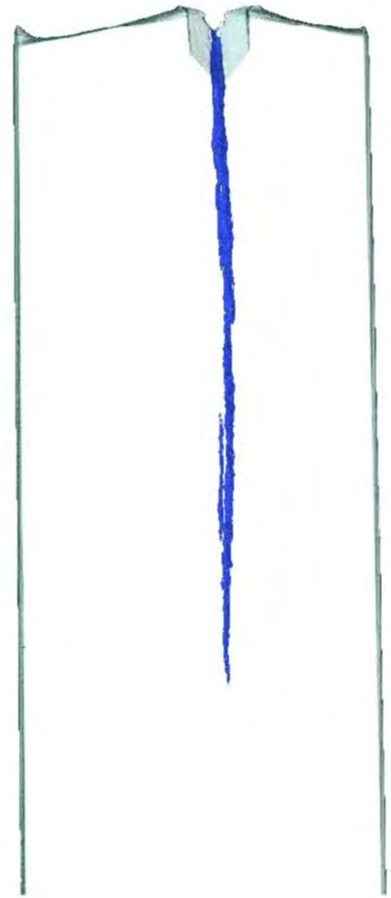
DCB – Crack Path: Tomography

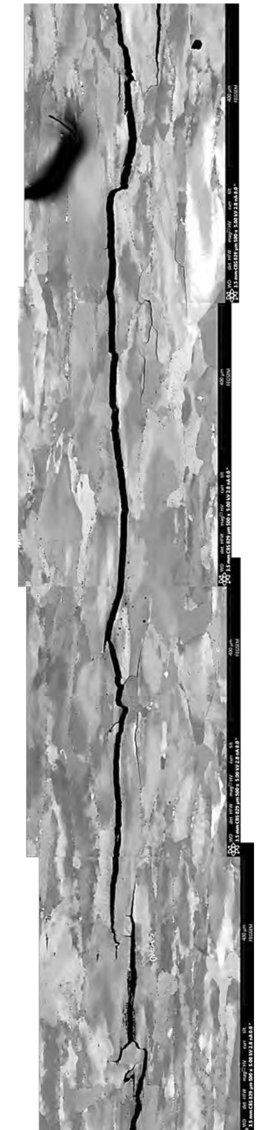


7050



7085





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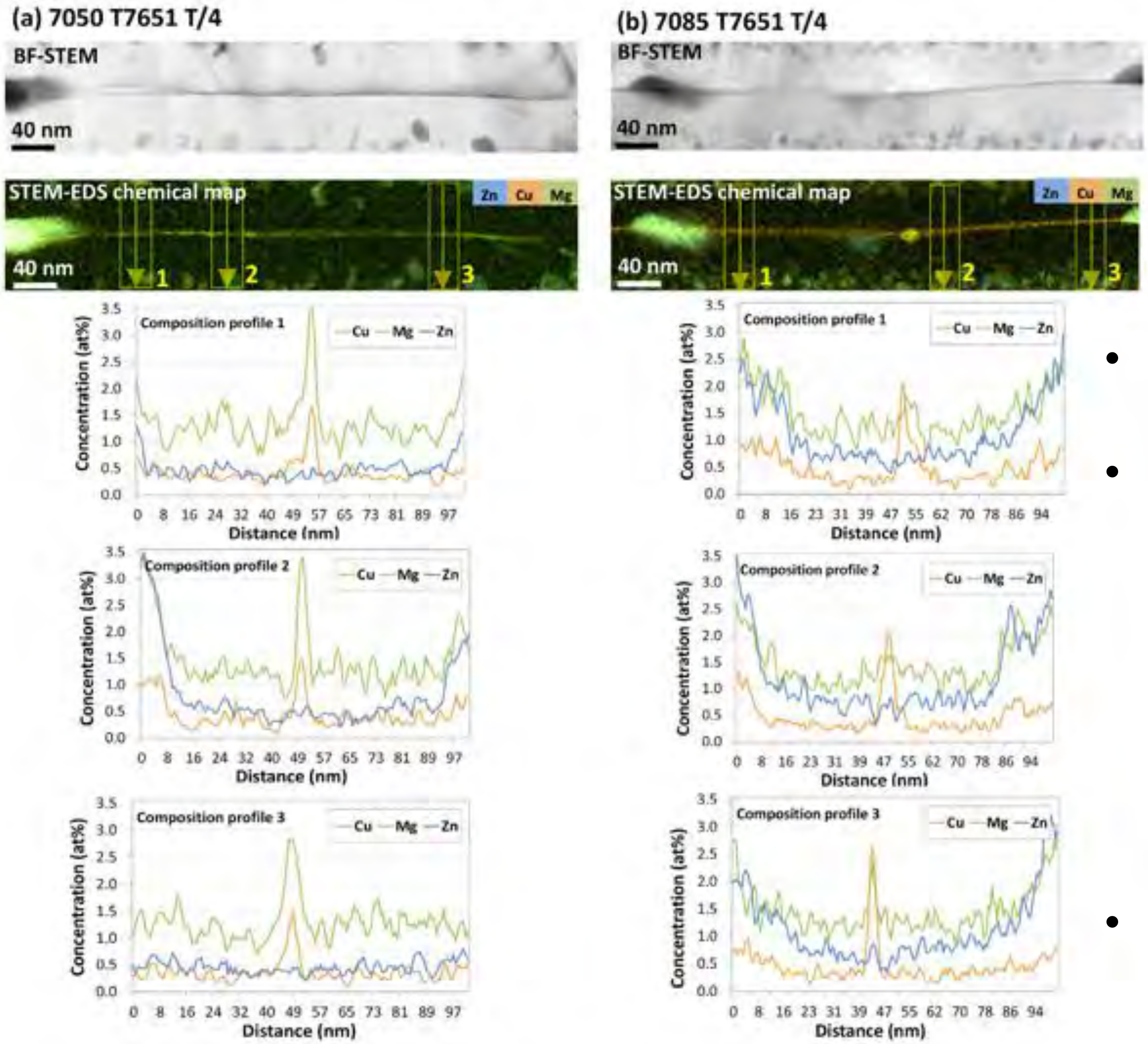
Grain Boundary Microstructure and Chemistry

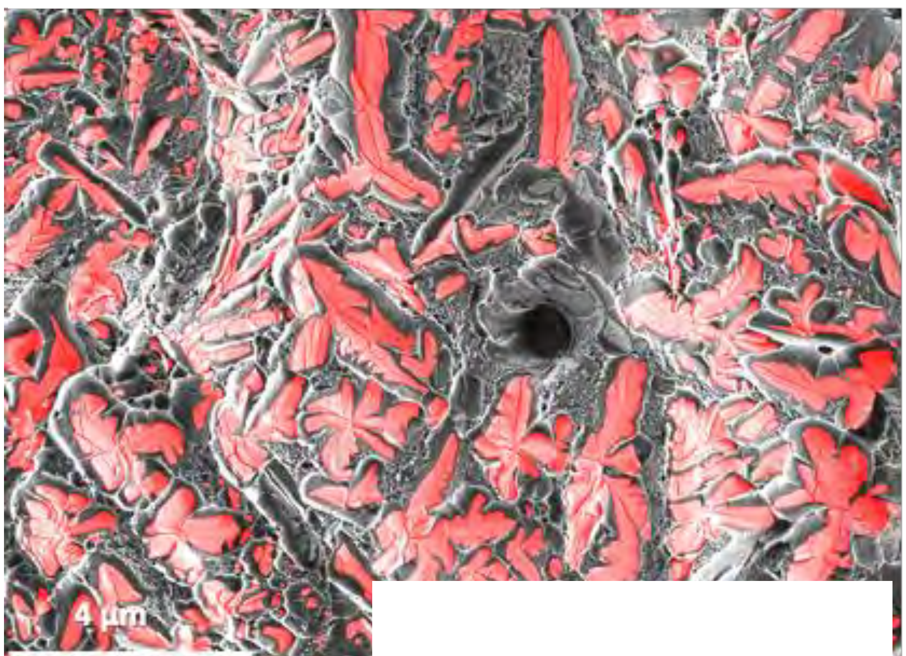


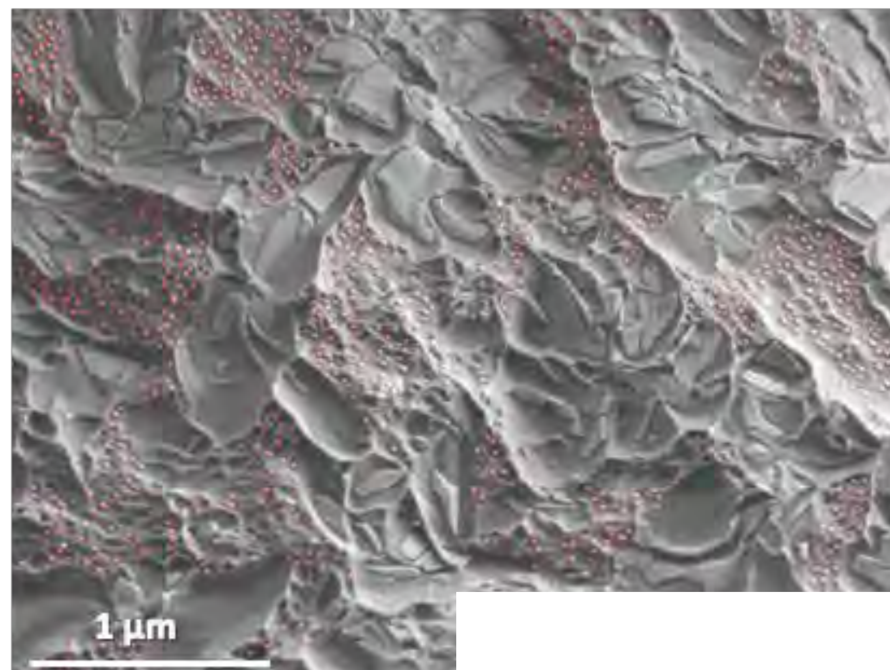
- No excess Zn at GBs in both alloys
- Difference in element segregation at GBs for 7050 vs 7085 quite small
  - 7050 higher Mg, lower Cu
  - 7085 lower Mg, higher Cu
- Does not directly explain H-EAC difference

GB Precipitates

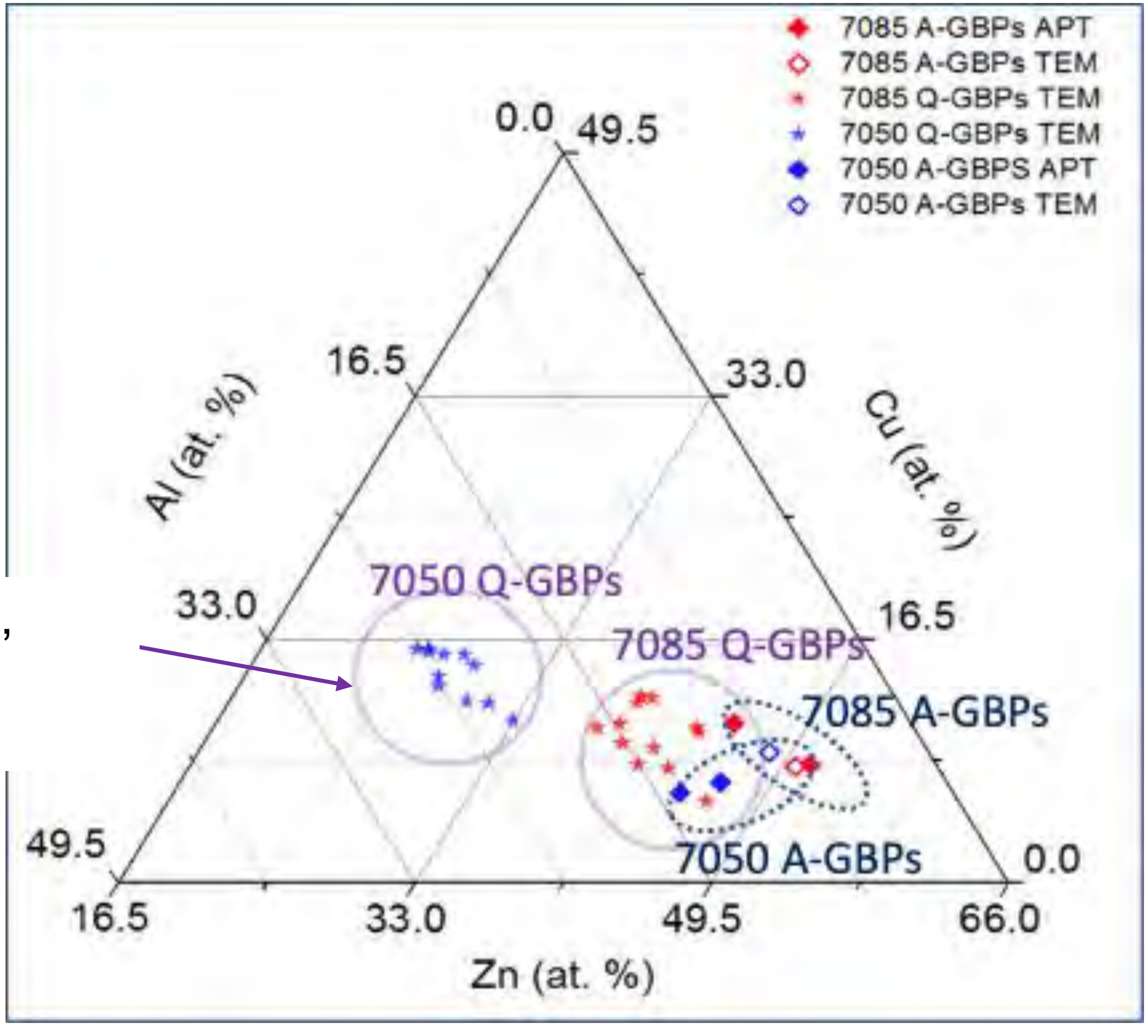
- Cold fracture to expose GB precipitates
- Identify 2 distinct GB ppt families
  - Quench induced
  - Ageing induced

AA7050 – 140 mm plate T/4





GB Precipitate Chemistry

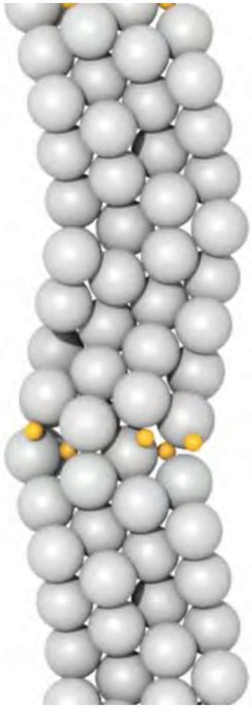


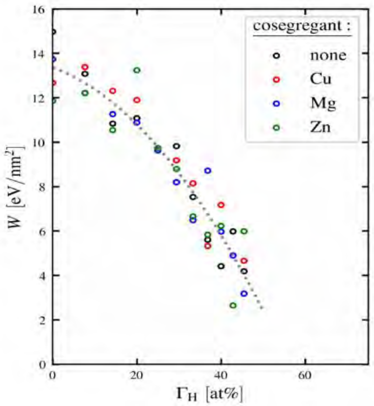
Higher Cu,

(7050)

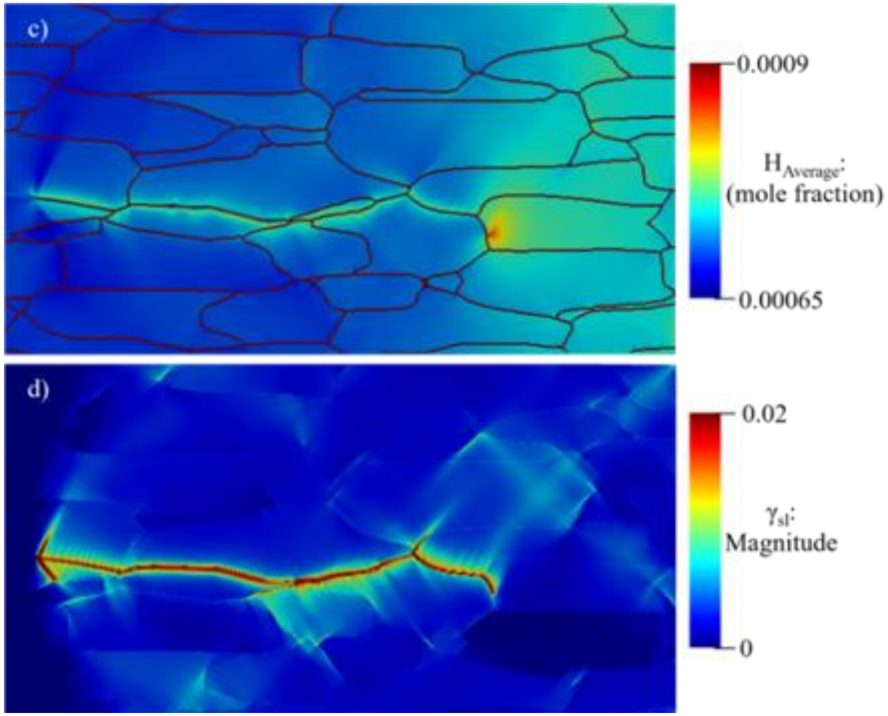
Modelling and Simulation

- Coupled phase field-crystal plasticity model for 7xxx EAC
  - Hydrogen production
  - Migration to crack tip
  - Stress concentration and fracture





Atomistic modelling
Work of separation of boundary with H concentration – considering segregant elements



Simulating hydrogen-controlled crack growth kinetics in Al-alloys using a coupled chemo-mechanical phase-field damage model
C. Grant, S. Roongta, T. L. Burnett, P. B. Prangnell, P. Shanthraj
Preprint available on-line (under review Acta Mater.)

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Summary: Critical Questions

- How has your organization bounded the problem?
  - Range of different test types in humid air (static load, DCB, slow strain rate) + microstructural investigation
- What are the key influencing factors?
  - **Temperature**, humidity, steady-state stress, stress concentration…
- What are the most critical questions?
  - Complete mapping of behaviour of new-gen 7xxx in humid air as f(T, humidity, stress)…
  - Explore effects of complex environments (e.g. marine) and loading scenarios
  - Complete understanding of potential mitigating strategies (processing/temper/geometry)
  - Development of **predictive** physical models to be used as design tools
- UoM has capacity to address these questions and share results
- Challenges with translation: complex phenomena – likely to require a **combination** of tests and distillation of complex models to simple rules
- Test methods (Henry Holroyd)
- New alloy development – based on mechanistic understanding of the process + test methods sensitive to humid air EAC

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Thanks for listening!

EIC Testing of Commercial Al-Zn-Mg-Cu Alloys

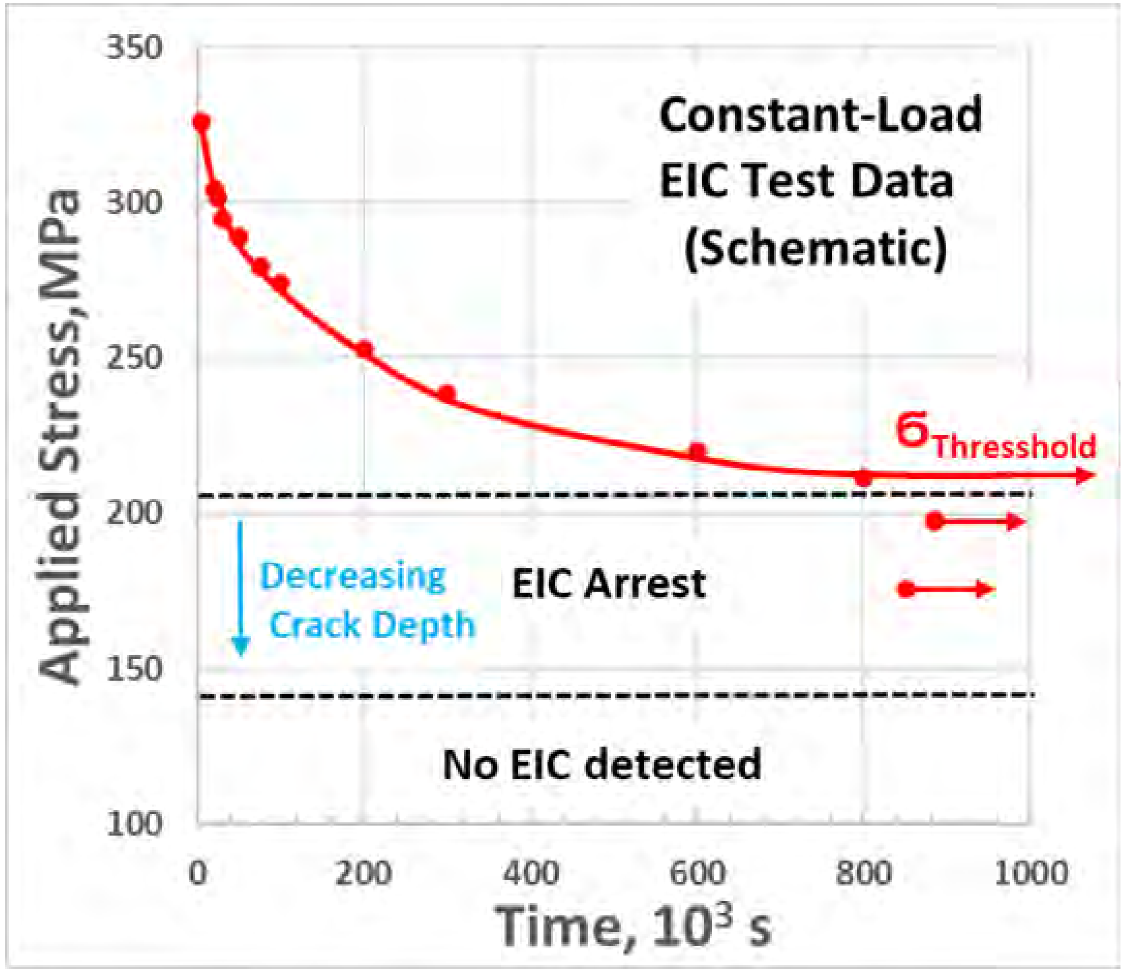
Henry Holroyd[1,2] Tim Burnett[1] John Lewandowski[2] Matthew Curd[1] Geoff Scamans[3,4]

1 - Department of Materials, The University of Manchester, M13 9PL, UK.
2 - Department of Materials Science and Engineering, Case Western Reserve University, Cleveland, OH 44106, USA.
3 - Innoval Technology, Banbury, Oxon OX16 1TQ, UK
4 - BCAST, Brunel University, Uxbridge, Middlesex UB8 3PH, UK.

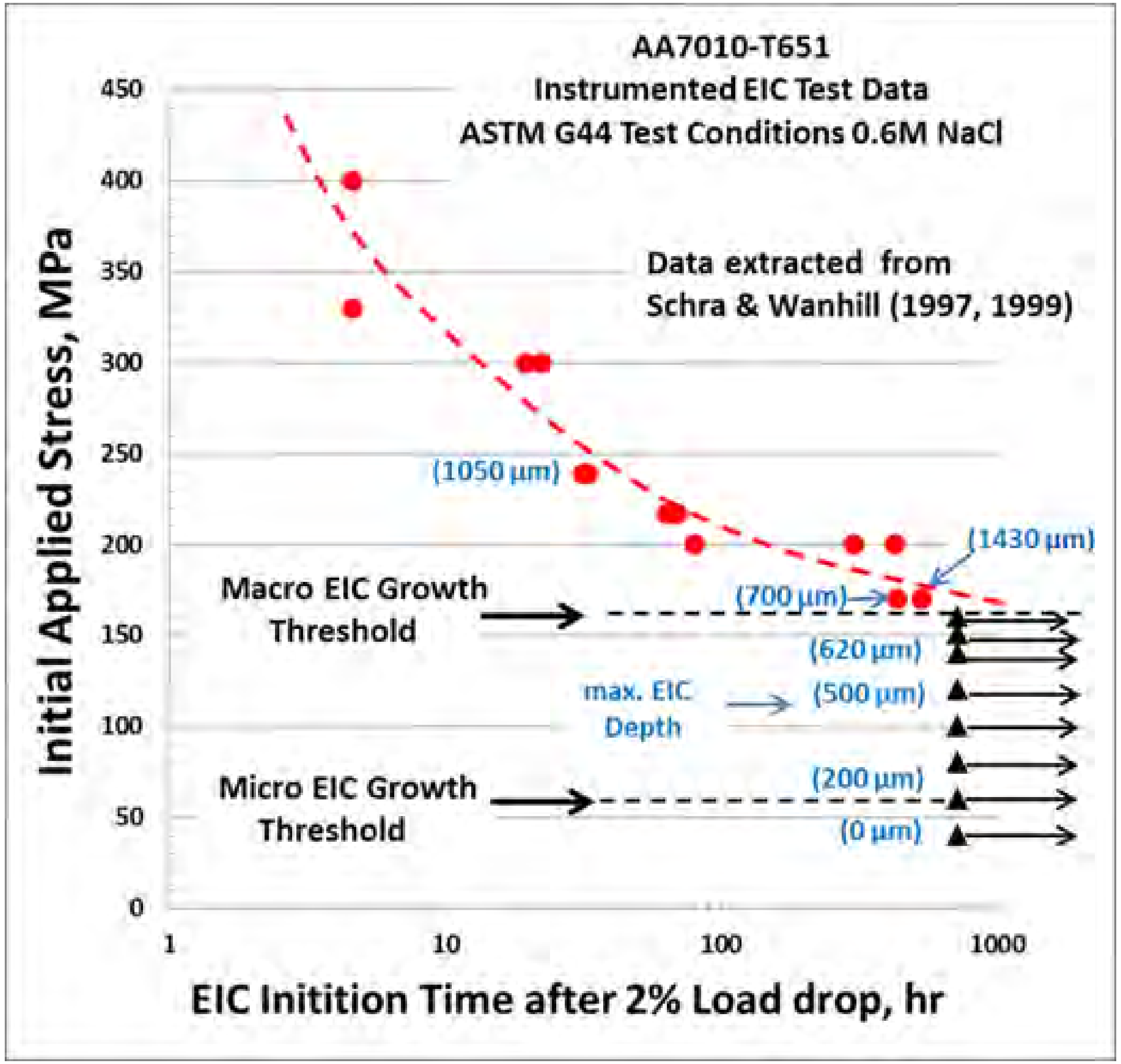
What is needed to improve EIC Testing?

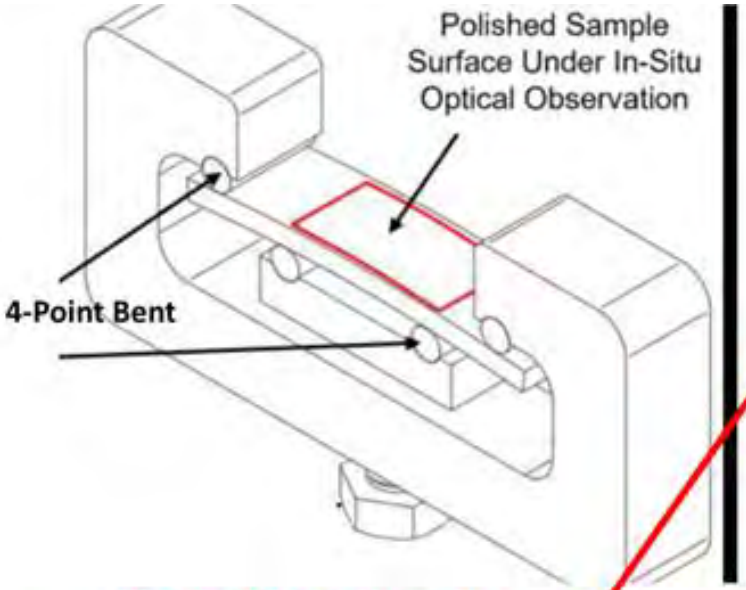
- Environmental test conditions relatable to ‘Service Conditions’
- Initial alloy surface conditions relatable or representative of those expected during service use
- An understanding how local strain-accommodation and Primary Creep rates influence EIC initiation and early crack growth at mechanical-driving forces below K_{IEIC} and Stress Thresholds.
- Clarification whether EIC ‘crack-arrest’ typically controls EIC initiation in structural applications

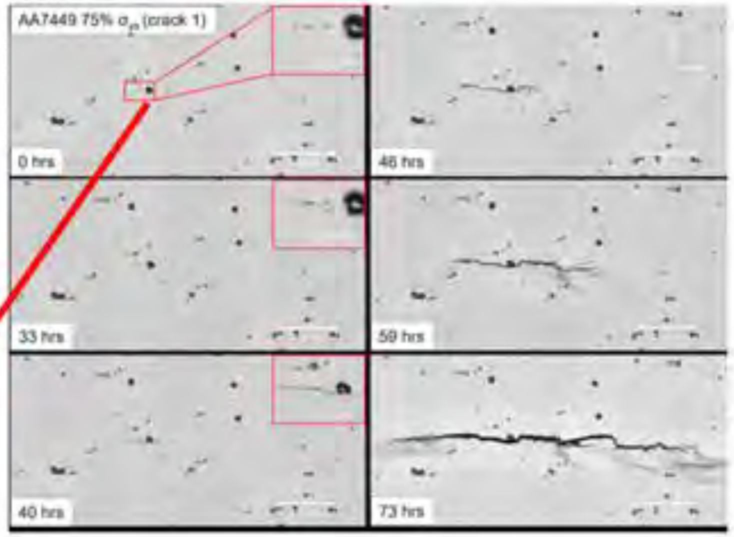
Constant-Load or Constant-Strain EIC Test



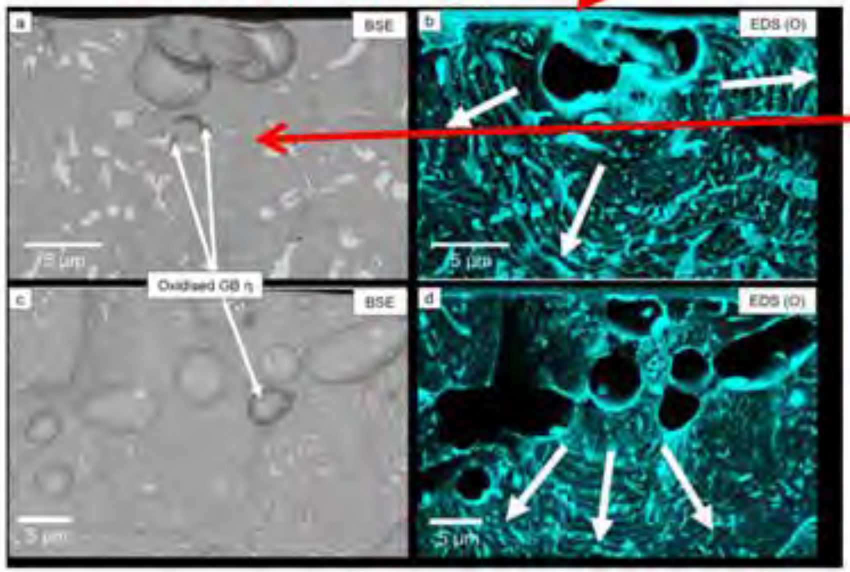
Instrumented Pseudo Constant Load Testing

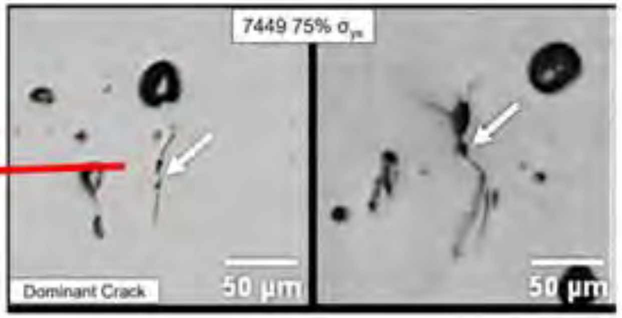






I[st] Crack Initiation site





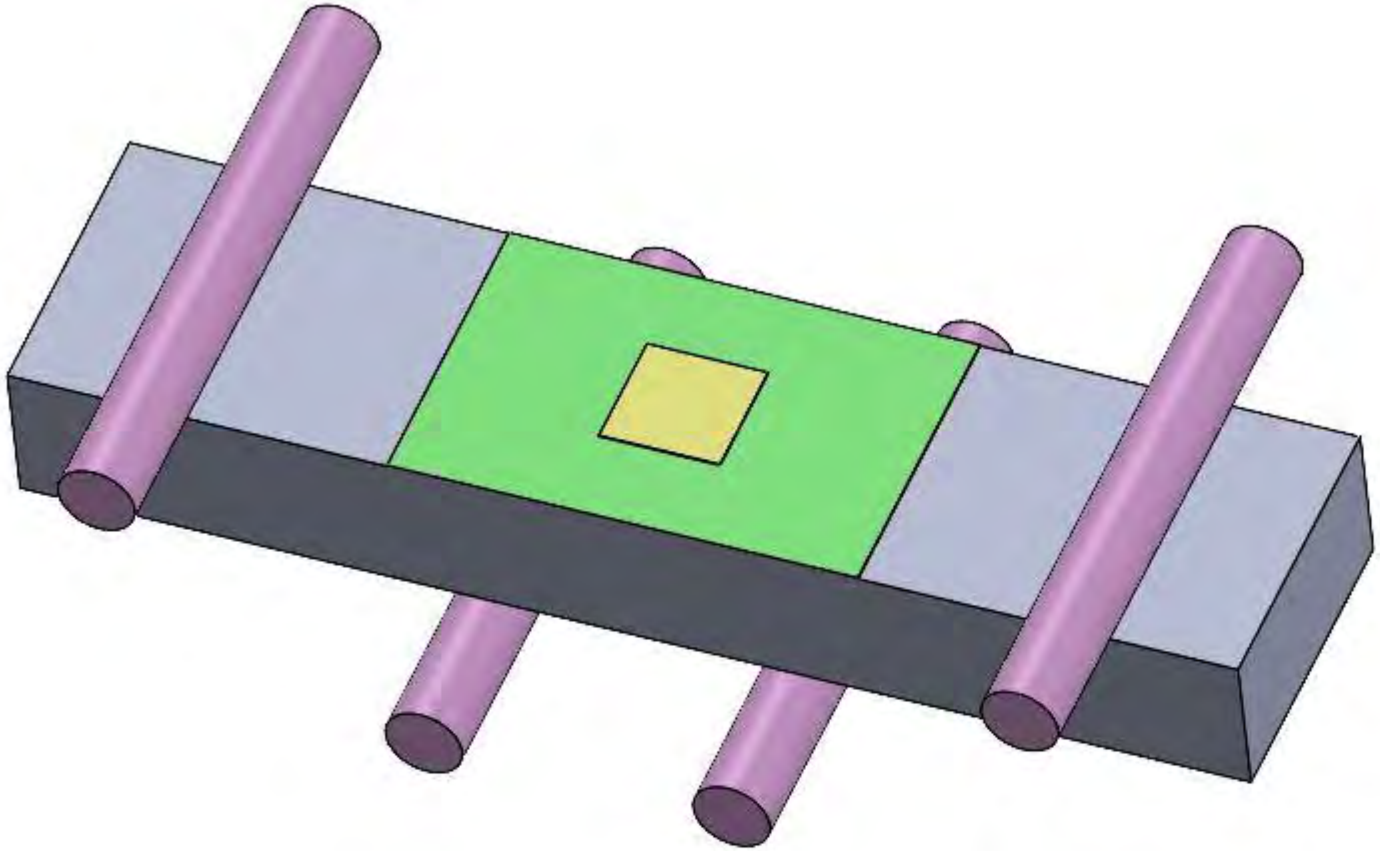
Ryan Euesden et al
Corrosion Science (2023)

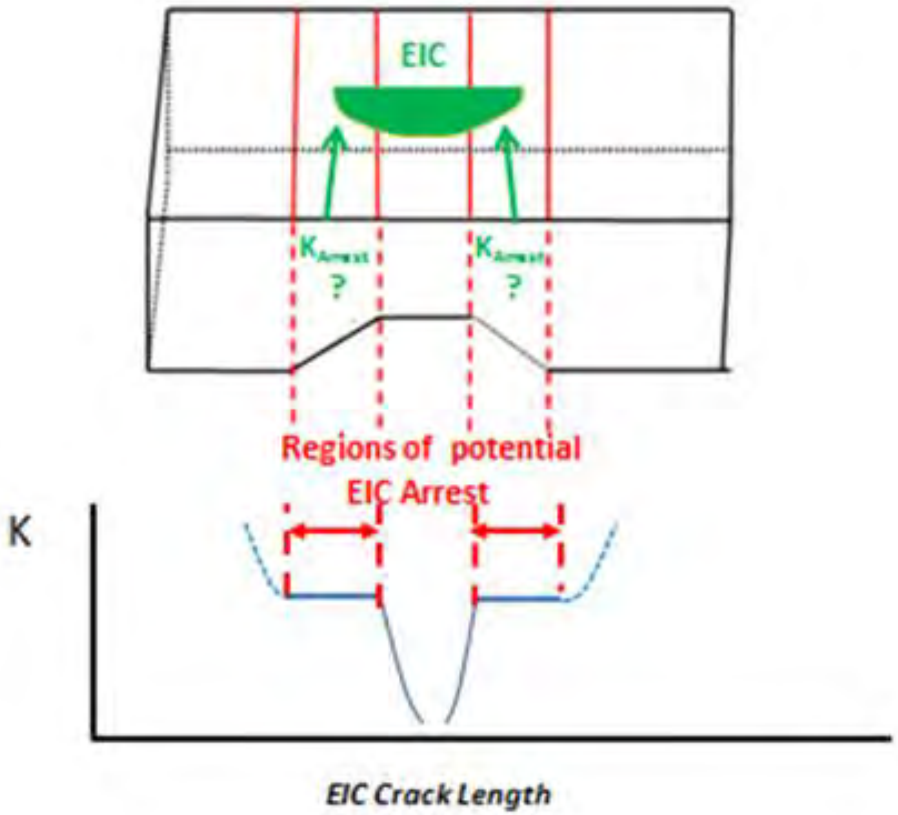
Characterization of EIC Crack-Arrest Characteristics

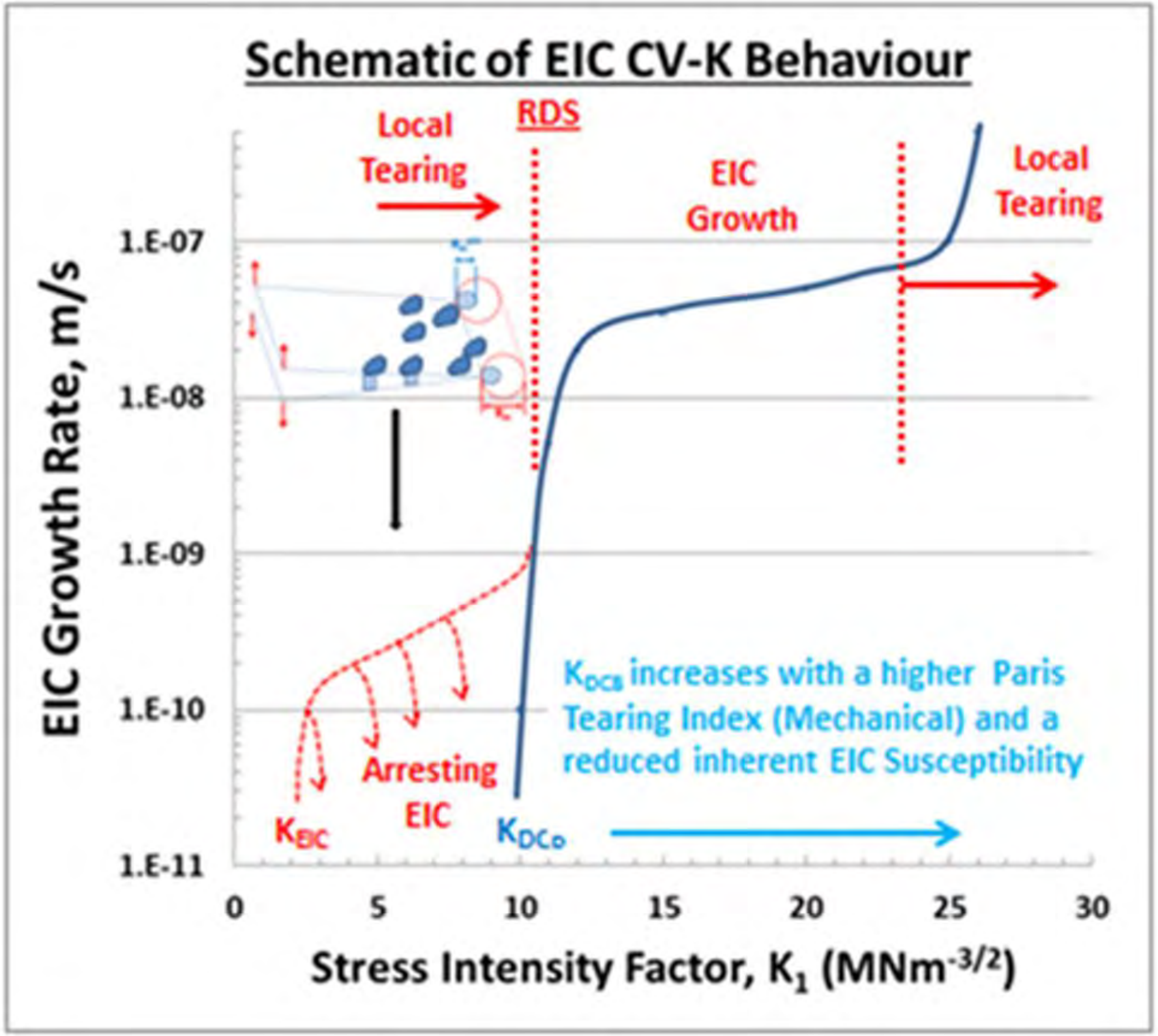
- Are EIC Crack-arrest characteristics at K's below K_{IEEC} relatable to an Al-Zn-Mg-Cu alloys inherent EIC resistance?

- If **Yes**, we can develop a 4-point bend EIC Test Method to characterize an alloys inherent EIC resistance under experimental conditions relatable to those for a commercial structural application.

- Success will require the use of appropriate initial surface condition for EIC initiation along with environmental and mechanical loading conditions relatable to expected service conditions




EIC
K_{Arrest}
?
K_{Arrest}
?
Regions of potential
EIC Arrest
K
EIC Crack Length



Schematic of EIC CV-K Behaviour
Local Tearing
RDS
EIC Growth
Local Tearing
EIC Growth Rate, m/s
1.E-07
1.E-08
1.E-09
1.E-10
1.E-11
K_DCB increases with a higher Paris Tearing Index (Mechanical) and a reduced inherent EIC Susceptibility
Arresting EIC
K_EIC
K_DCB
0
5
10
15
20
25
30
Stress Intensity Factor, K_1 (MNm^-3/2)

New Approach to evaluate EIC propensity

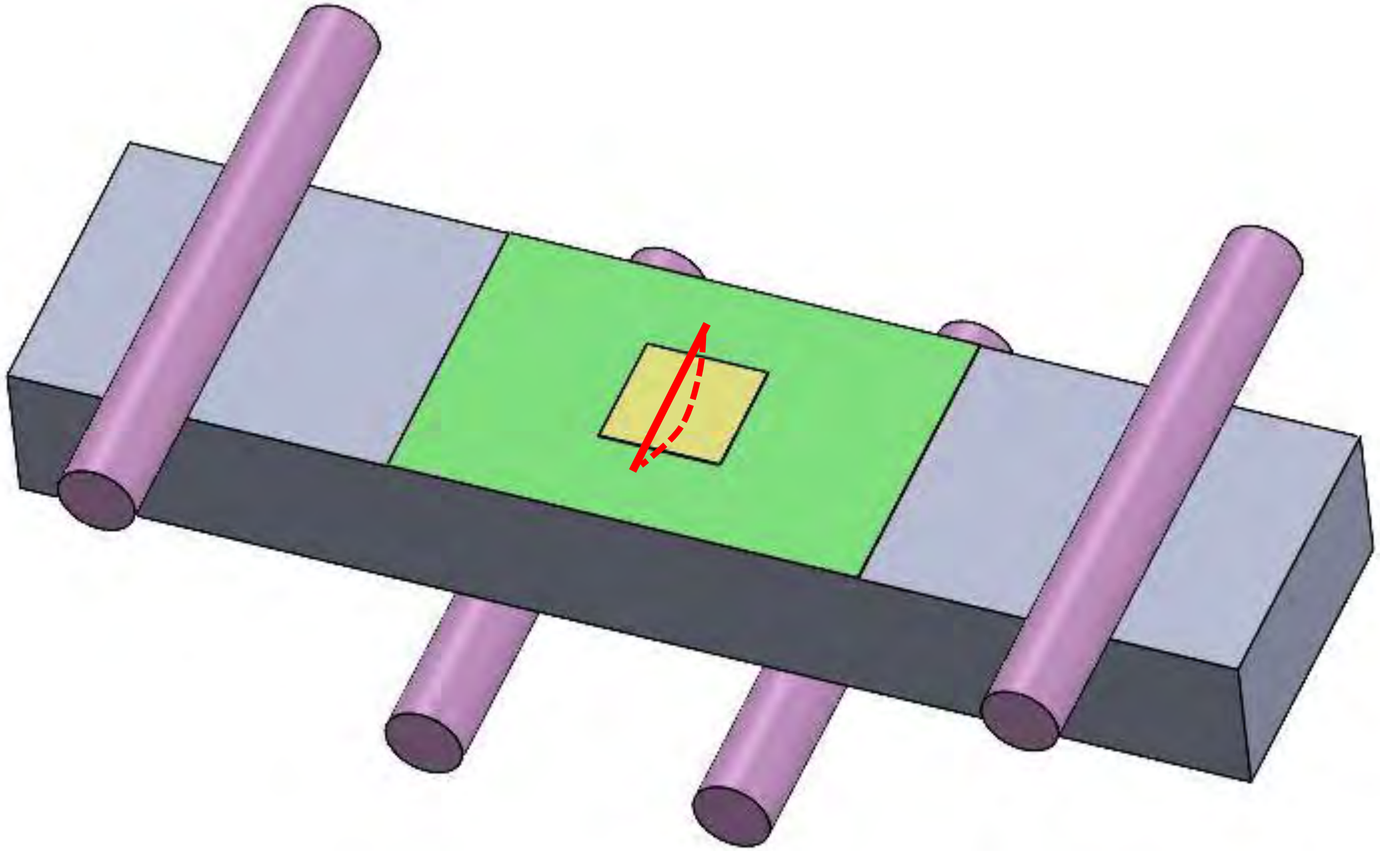
- Determine if EIC Crack-arrest behavior at K's below K_{IEIC} is related to an Al-Zn-Mg-Cu alloys inherent EIC resistance.

- Quantify the role local 'strain-accommodation' plays during EIC initiation and early-stage crack growth

Metal/environment systems where exhaustion of primary creep ahead of exposure of a stressed sample to an EIC environment can either prevent or significantly increase minimum mechanical driving force ($\sigma_{Thresshold}$ or K_{IEIC}) required for EIC initiation.

Alloy	Loading Conditions	Environment Conditions	Temperature	T_m (T/T_{mp}) °K	Reference
Ti-7Al-2Cb-1Ta Annealed YS = 706 MPa, UTS = 823 MPa, K_{IC} = 121 $MNm^{-3/2}$	Fatigue Pre-cracked SEN cantilever bend, Constant Load	Lab Air (30% RH) or 0.53M NaCl, FCP	RT	0.15	Leckie 1967
Mg-7Al	Constant Load Smooth Tensile Specimen	Aq. CrO_4^{2-}/NaCl	RT	0.34	Wearmouth et al. 1973
26Cr-1Mo Ferritic Stainless Steel	Constant Load Smooth Tensile Specimen	42% LiCl + Thiourea -500 or -460 mV (SCE) De-aerated	140 °C	0.25	Kwon et al. 1992
Annealed 304 Stainless Steel K_{IC} = 86 $MNm^{-3/2}$	Constant strain Notched WOL Constant Load SEN both with 0.2 mm notch root radius	42% $MgCl_2$	143 °C	0.25	Gu et al. 1994
As-quenched NiCrMoV Rotor Steel, YS=1250 MPa	Double Cantilever Beam, Fatigue Pre-cracked Constant Load & Constant Strain	Dry Air (Silica–gel) Distilled Water	22 °C	0.17	Rieck et al. 1989
As-quenched 4340 high strength martensitic steel, YS 1700 MPa	Double Cantilever Beam, Fatigue Pre-cracked Constant Load & Constant Strain	Dry Air (Silica–gel or P_2O_5) Distilled Water	22 °C	0.17	Rieck et al. 1989
C-Mn Pipeline Steel	Constant Load Fatigue Pre-cracked SEN cantilever bend,	1M Na_2CO_3 + 1M $NaHCO_3$ -900 or -650 mV (SCE)	75 °C	0.2	Parkins 1979

Holroyd et al (2024)



Measurement of Environmentally Assisted Cracking in Atmospheric Tests

Fritz Friedersdorf

Carly Cocke

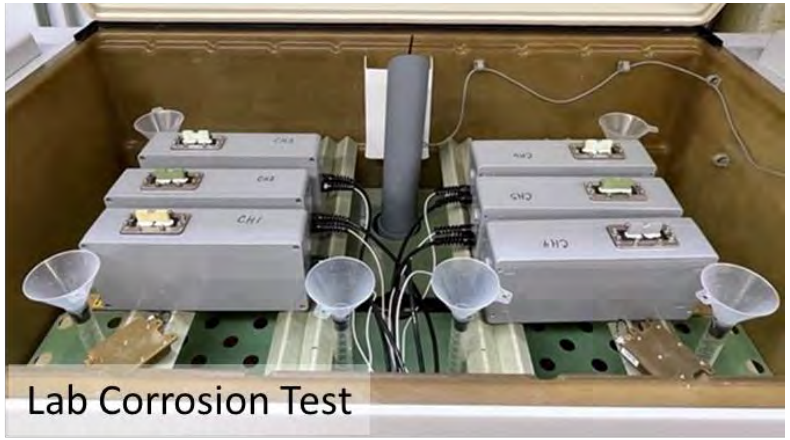
AFRL-FAA Technical Interchange Meeting (TIM) on Environmentally Assisted Cracking (EAC) / Stress Corrosion Cracking (SCC) of High-Strength 7000 Series Aluminum Alloys

5 November 2024

Applied Research and Development

Continuous *in situ* monitoring and mechanical testing of aluminum alloys in corrosive atmospheres

- Relevance of accelerated laboratory test to outdoor exposure
- Significance of galvanic couples and crevice conditions
- Risk of chromate elimination from protective coatings for EAC and ASIP assumptions



Combined-effects laboratory and relevant environment testing

- Environmental conditions
  - RH, temperature, and conductance (salt loading)
- Compliance measurements used to estimate crack growth

ACUITY corrosion technology

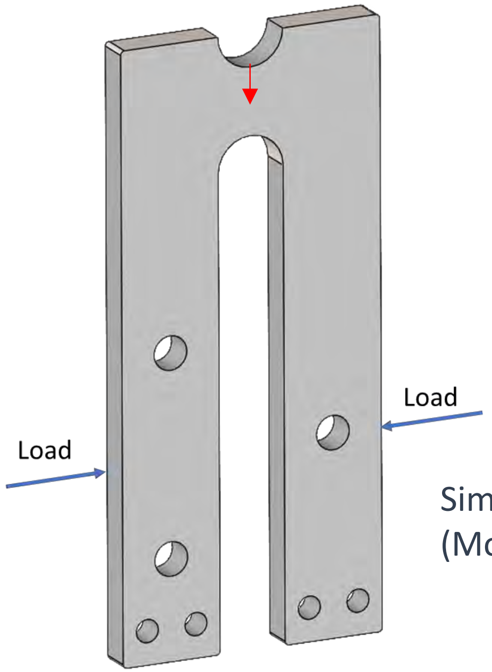
Measurement Sample and Test System

Fracture sample designed to accommodate range of alloy orientations, crevice former, and surface finishes

- No need for a precrack

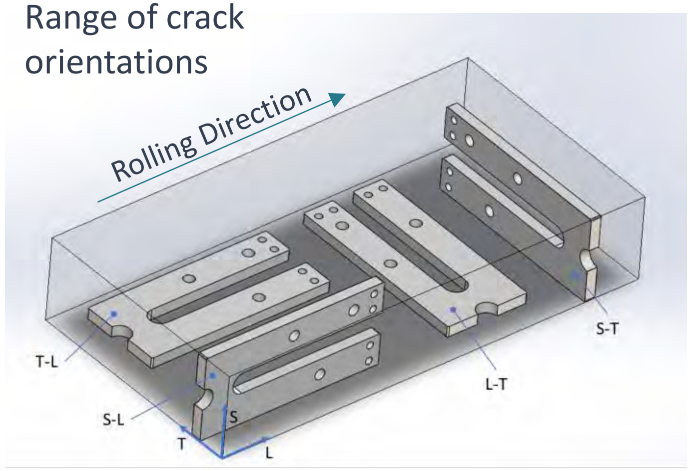
Mechanical test system for continuous measurement of cracking throughout a combined effects test

Double cantilever beam fracture sample

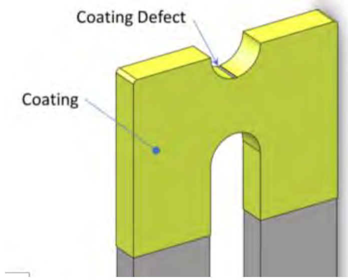


Simple loading (Mode I)

Range of crack orientations

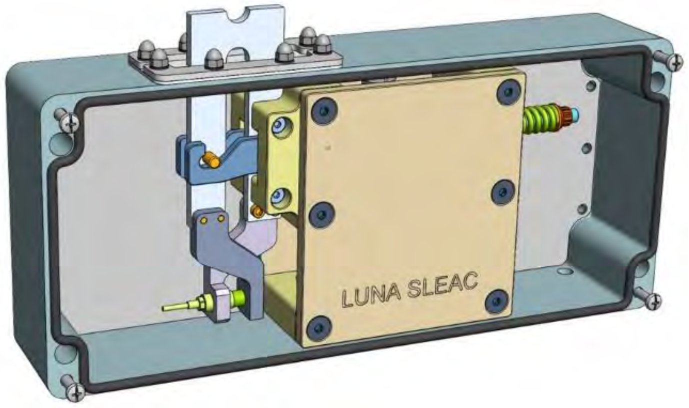


Sample can be easily coated



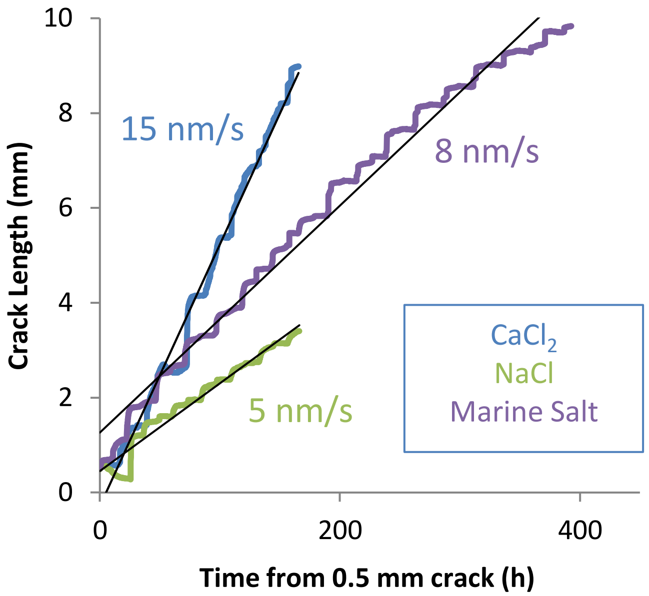
Enclosure protects load frame and electronics from environment

Galvanic crevice former



AA7075-T651
S-L Crack

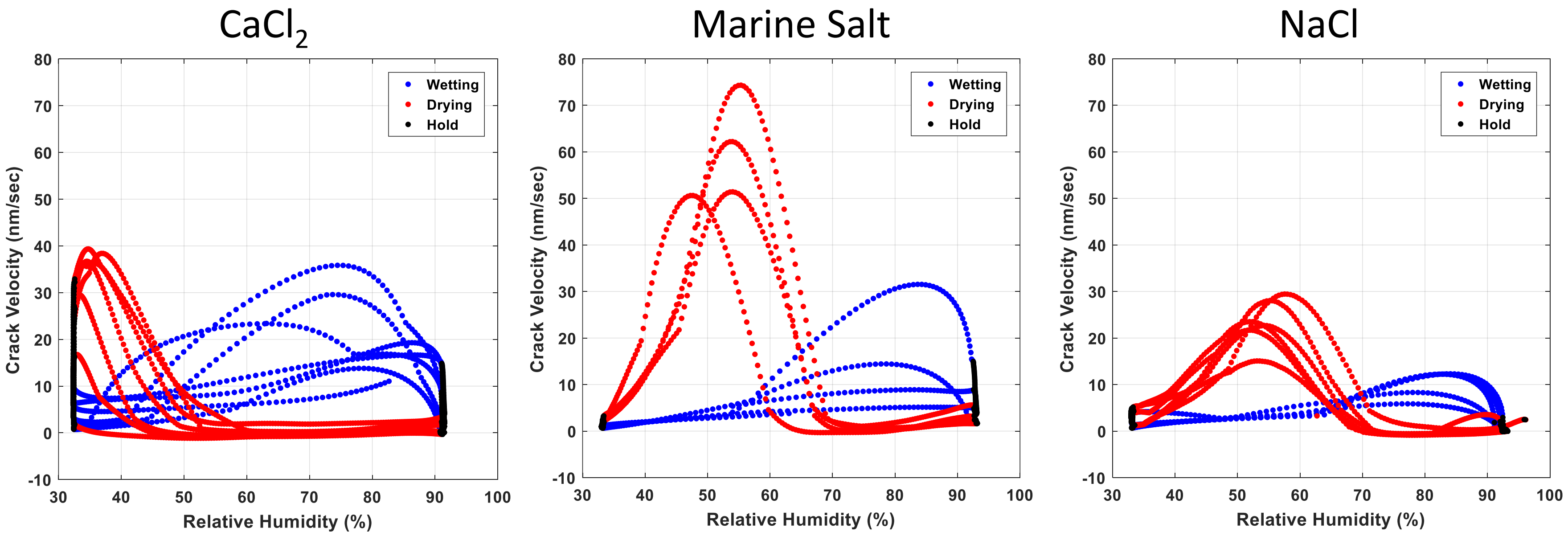
Influence of RH and Salt Chemistry



High transient crack growth rates for AA7075-T651 occur preferentially during drying (decreasing RH)

- Hygroscopic properties of the salts influence RH dependence

Results consistent with testing that emphasizes cyclic wetting and drying (ASTM G47)



AA7075-T651
S-L crack orientation
Crevice Former: 316SS

ACUITY corrosion technology

Galvanic Crevice

Static loading tests using a statistical representation of a RH diurnal cycle

Measure galvanic current (aluminum and SS316) and crack growth rate (CGR)

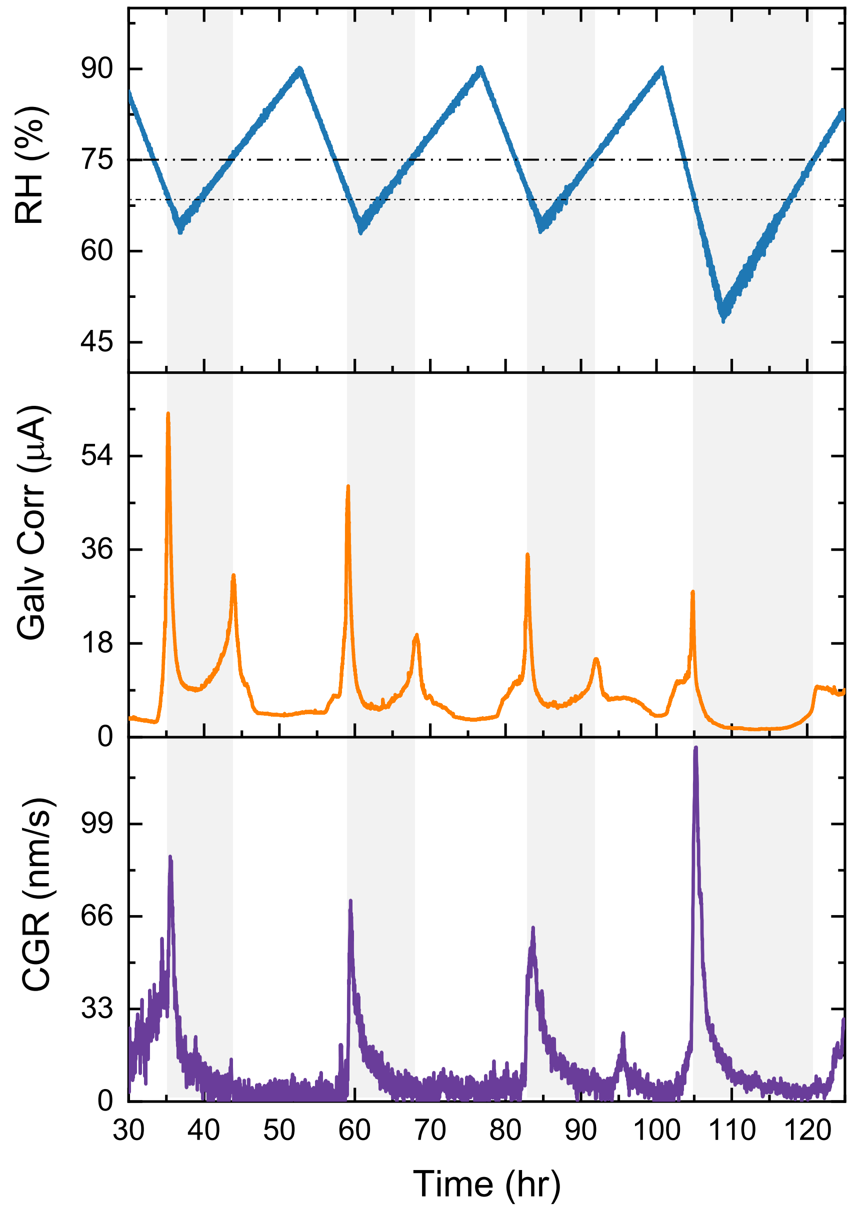
Galvanic corrosion rate peaks during both drying and wetting

- ORR dependent on thin film conditions

CGR peaks when humidity decreases (drying), and cracking is relatively insensitive to wetting

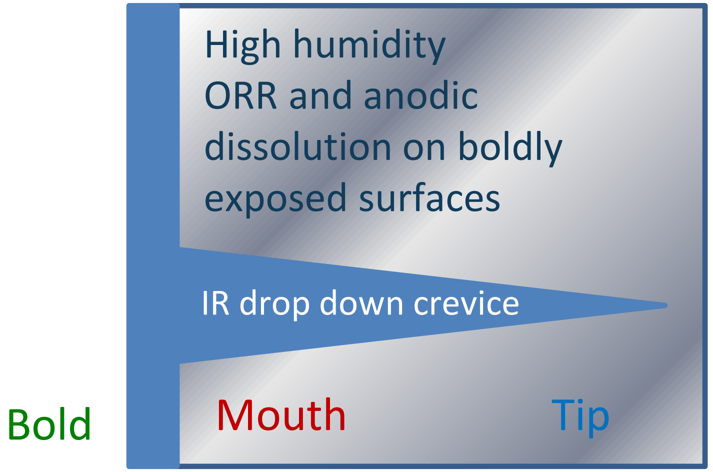
- Drying focuses corrosion into the crevice/crack

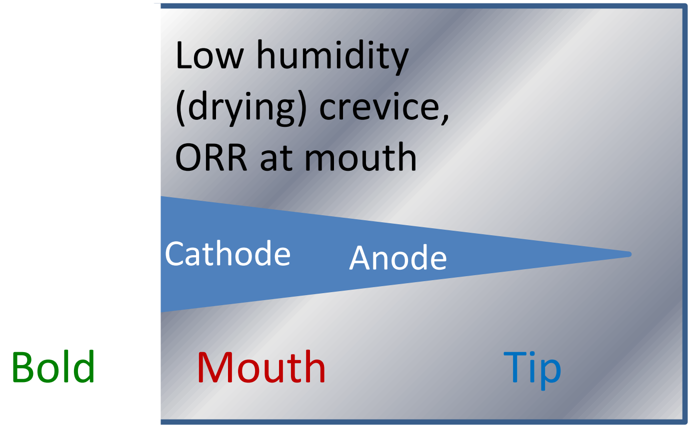
Agnew, ASTM STP 1643, 2023



ACUITY corrosion technology

Mechanistic Interpretation of Atmospheric EAC

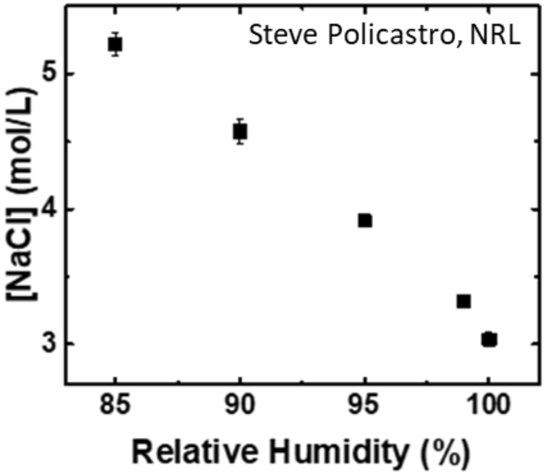




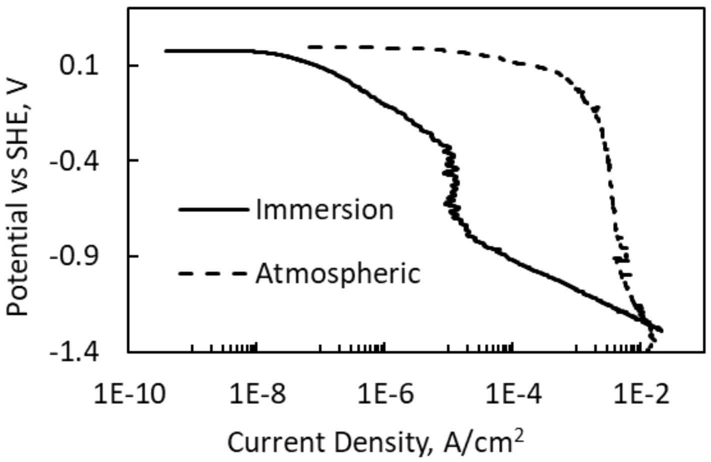
Variable chemistry, reaction rates, and spatial distribution of electrolytes

- High salt concentrations
- Increased ORR for thin films
- Current distribution on surfaces and crevices

High salt concentration



High thin film ORR



BEASY

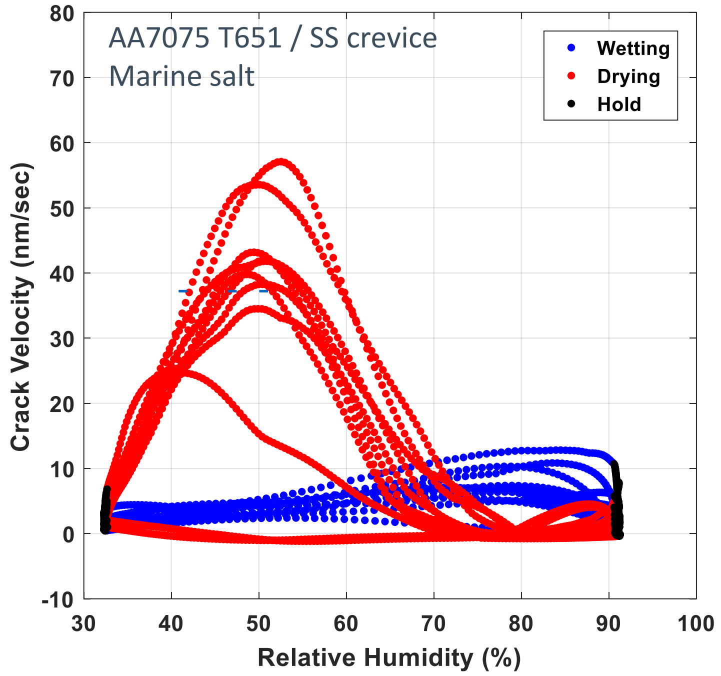
BEASY doing 3-D modeling of fracture sample and current distribution for specific environmental conditions

ACUITY corrosion technology

Mechanistic Interpretation of Atmospheric EAC

During drying electrolytes and corrosion currents are localized to crevices and cracks (last areas to dry off)

- ORR at mouth
- Anodic dissolution near the ORR mouth area
    - Hydrolysis lowers pH and promotes hydrogen ion reduction
- At the crack tip, hydrogen ion reduction may be favored
    - Proton reduction may increase pH at crack tip



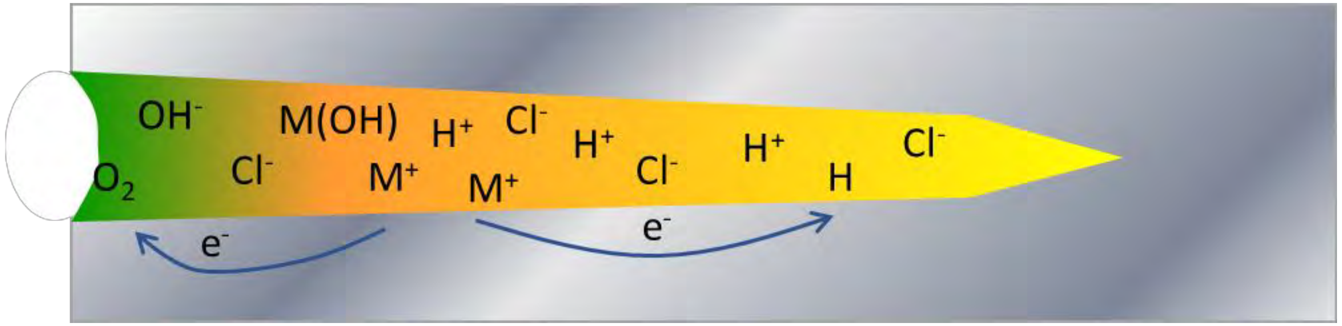
Consistent with HEAC described by Gangloff, Cooper, and Kelly

$$O_2 + H_2O + 4e^- \rightarrow 4OH^-$$

$$M \rightarrow M^{n+} + ne^-$$

$$M^{n+} + zH_2O \rightarrow M(OH)_z^{(n-z)+} + zH^+$$

$$H^+ + e^- \rightarrow H_{ads}$$

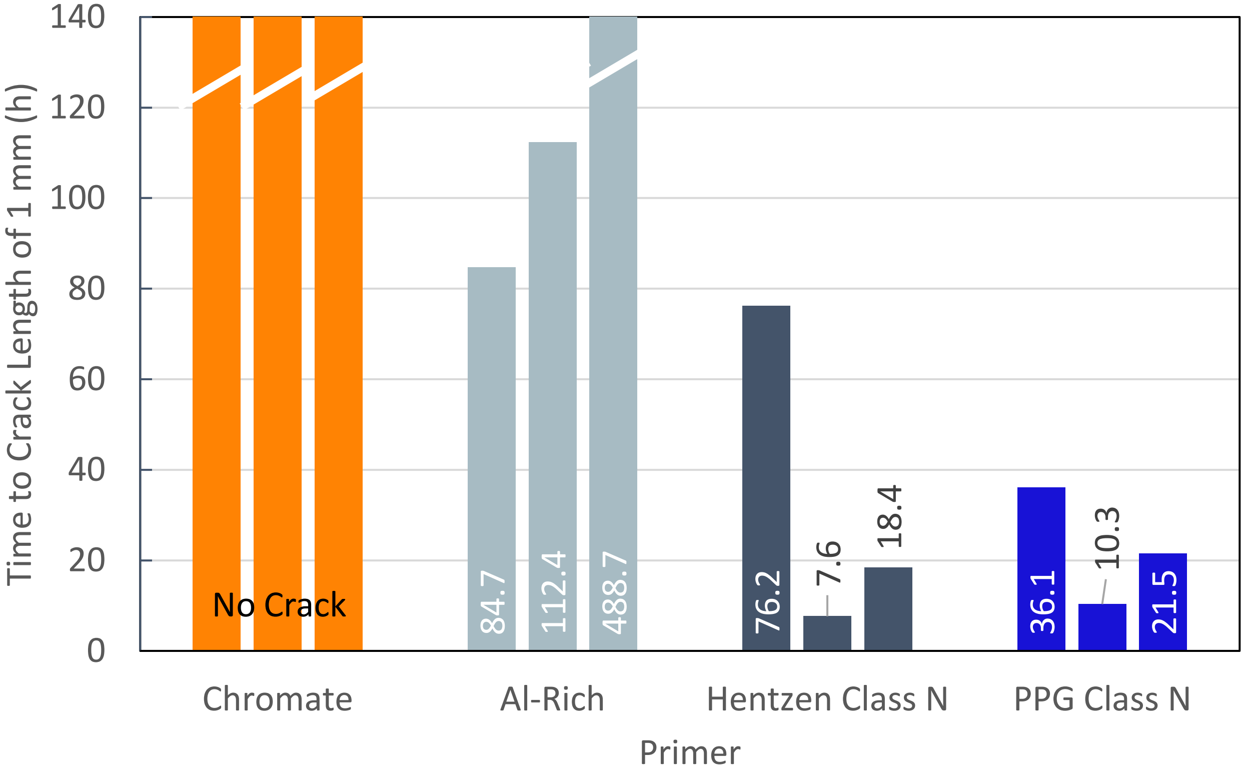


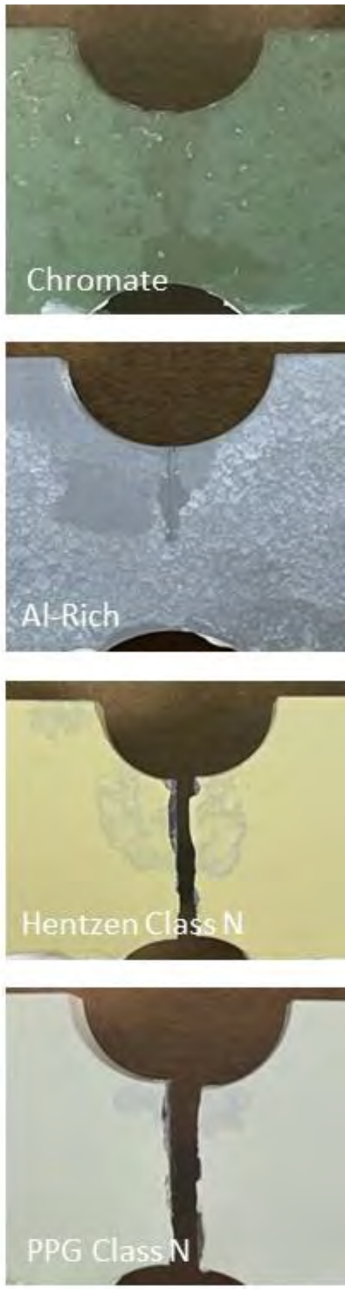
ACUITY corrosion technology

Protective Properties of Coatings

- Susceptible aluminum alloy facture samples have been used to evaluate the EAC protective properties of coatings
- Working with NAWCAD to refine method and update AMPP TM21449-2021
- Need to verify results in outdoor exposure testing

AA7075-T651
MDACT
Applied load of 30% YS
(140 MPa, 325 N)
S-L crack orientation





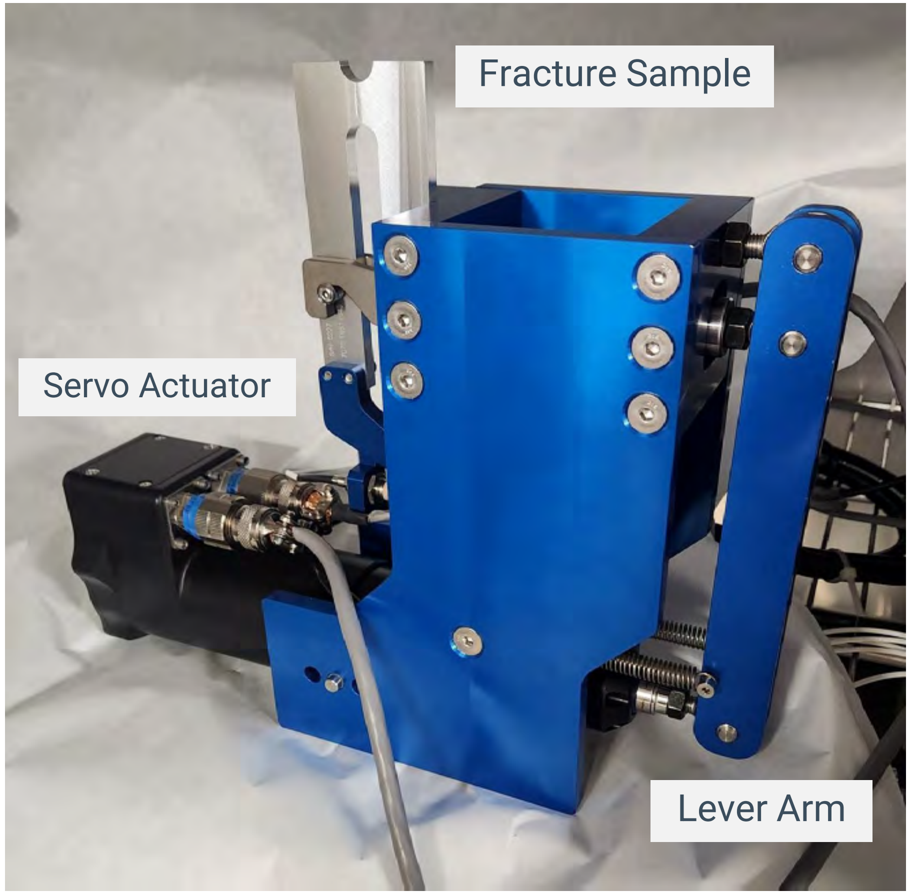
Dynamic EAC - Load Frame with Actuation

Dynamic EAC system for testing in laboratory and outdoor environments

DEAC load frame:

- Force Range: 0 – 1000 N [223 lb_f]
- R-ratio: 0 to 1
- Frequency: constant load to 5 Hz sine wave

For reference: 1000 N produces 90% YS on smooth gauge AA7075-T651 DCB sample



ACUITY corrosion technology

Moving Forward

Conducting outdoor EAC testing at Battelle FMRF to verify RH and load dependencies in relevant environments

- Combined with environment, contaminant, and corrosivity measurements for modeling corrosion and cracking

Perform DOE with a wide range of coatings (Cr and non-Cr) in collaboration with NAWCAD using MDACT

- Results will be used to revise AMPP TM21449-2021
- Validate coating performance results in outdoor tests

Initiate corrosion fatigue testing using similar conditions as SCC work (RH, salt, crack orientation, galvanic coupling)

- Dynamic environmental and mechanical processes

ACUITY corrosion technology

ACUITY corrosion technology

Fritz Friedersdorf

https://acuitycorrosion.com/

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+1 540 808 8947

MATERIALS ENGINEERING

AFRL-FAA EAC TIM

SOUTHWEST RESEARCH INSTITUTE®

11/5/2024

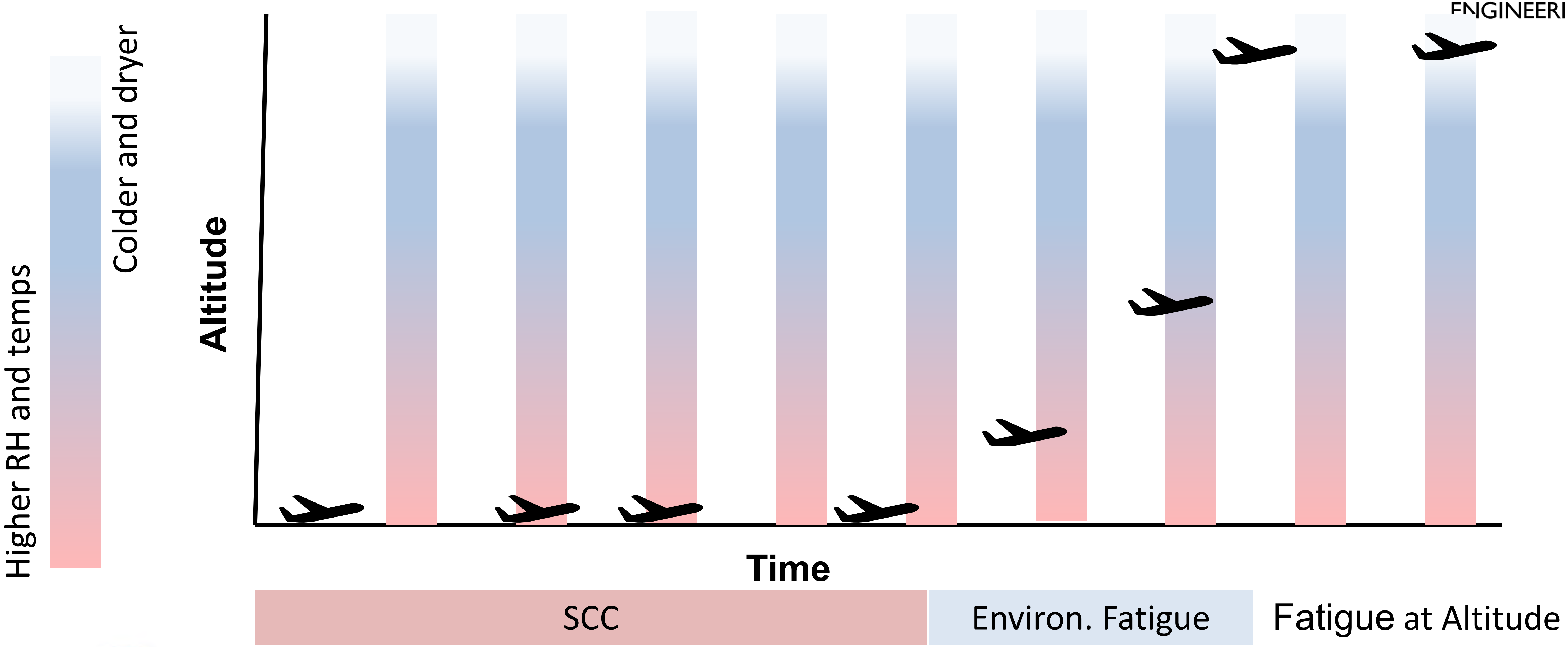
Several ways to think of EAC on aircraft

MATERIALS ENGINEERING

- Historically
  - Effects of environment were accounted for in model uncertainty
  - This has worked well and improved with experience
- Concerns arose because of
  - Aloha flight 243
  - Chromate elimination
- How do we better account for corrosion in structural integrity?
  - Affect of damage profile on subsequent fatigue (sequential approach)
  - Affect of environment directly on CGR (parallel approach)

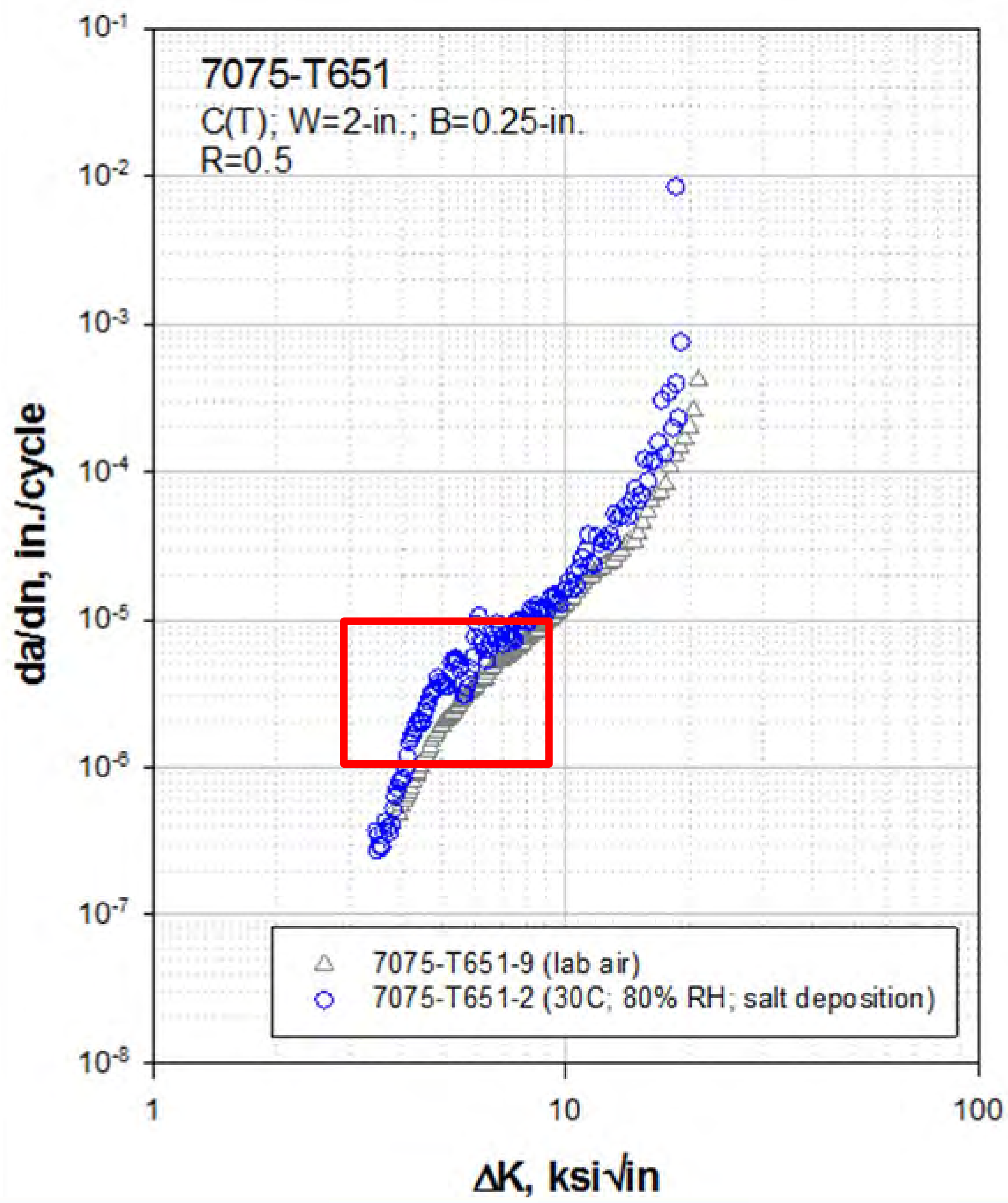
Where might environment have the largest effect on crack growth?

MATERIALS ENGINEERING



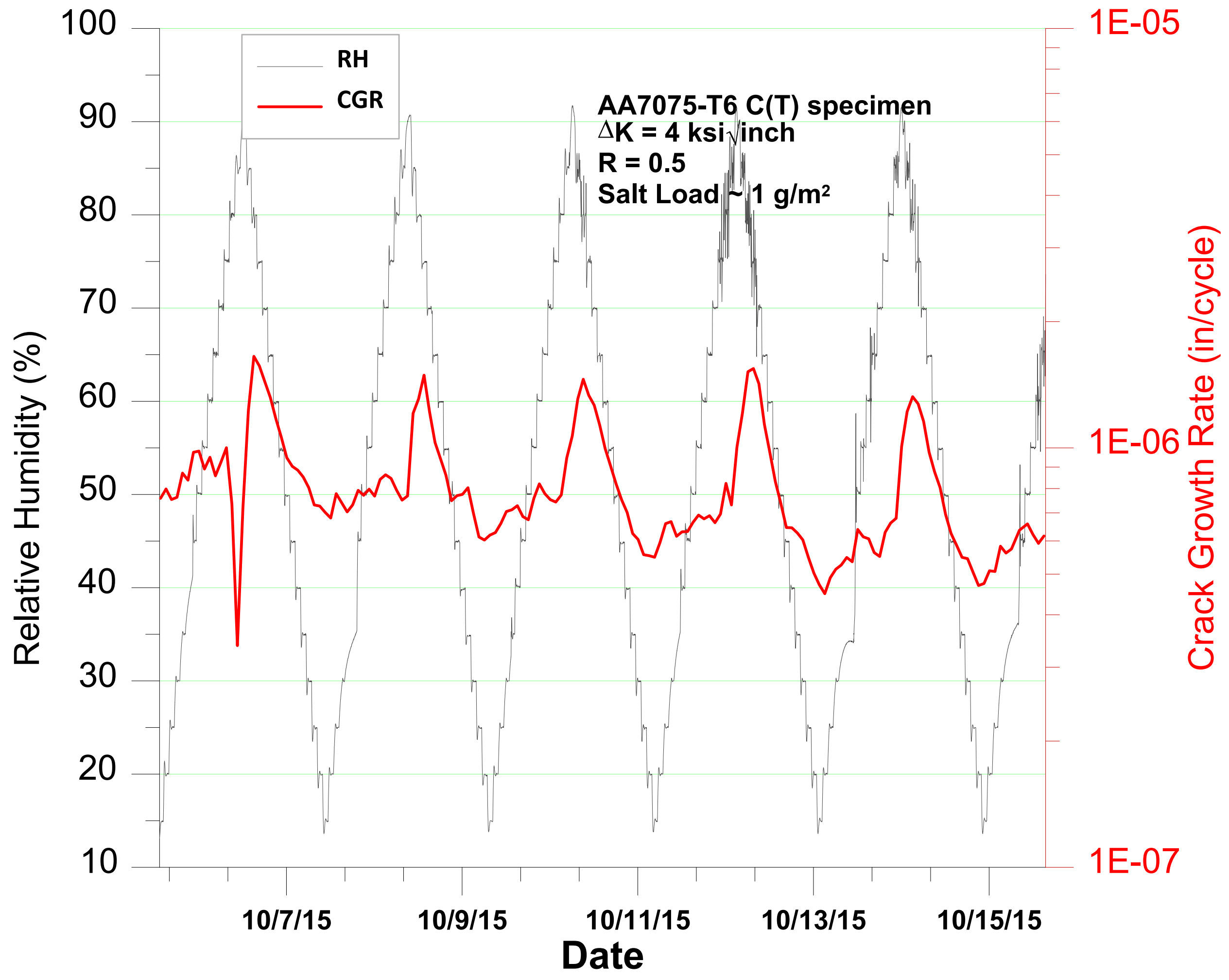
Effects of RH don't look minor when viewed as da/dN vs ΔK.

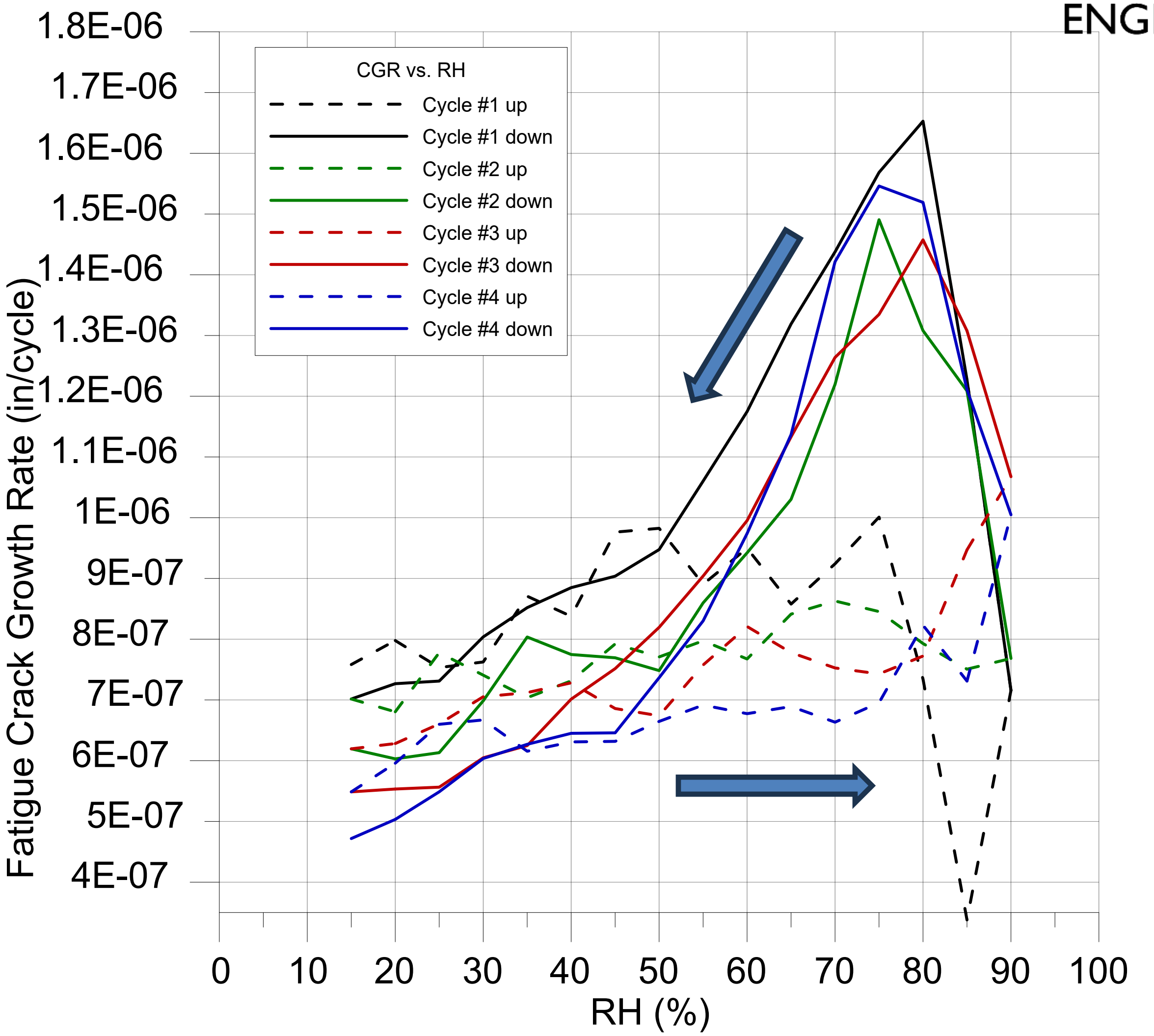
MATERIALS ENGINEERING



Cyclic wetting and drying affect fatigue

MATERIALS ENGINEERING



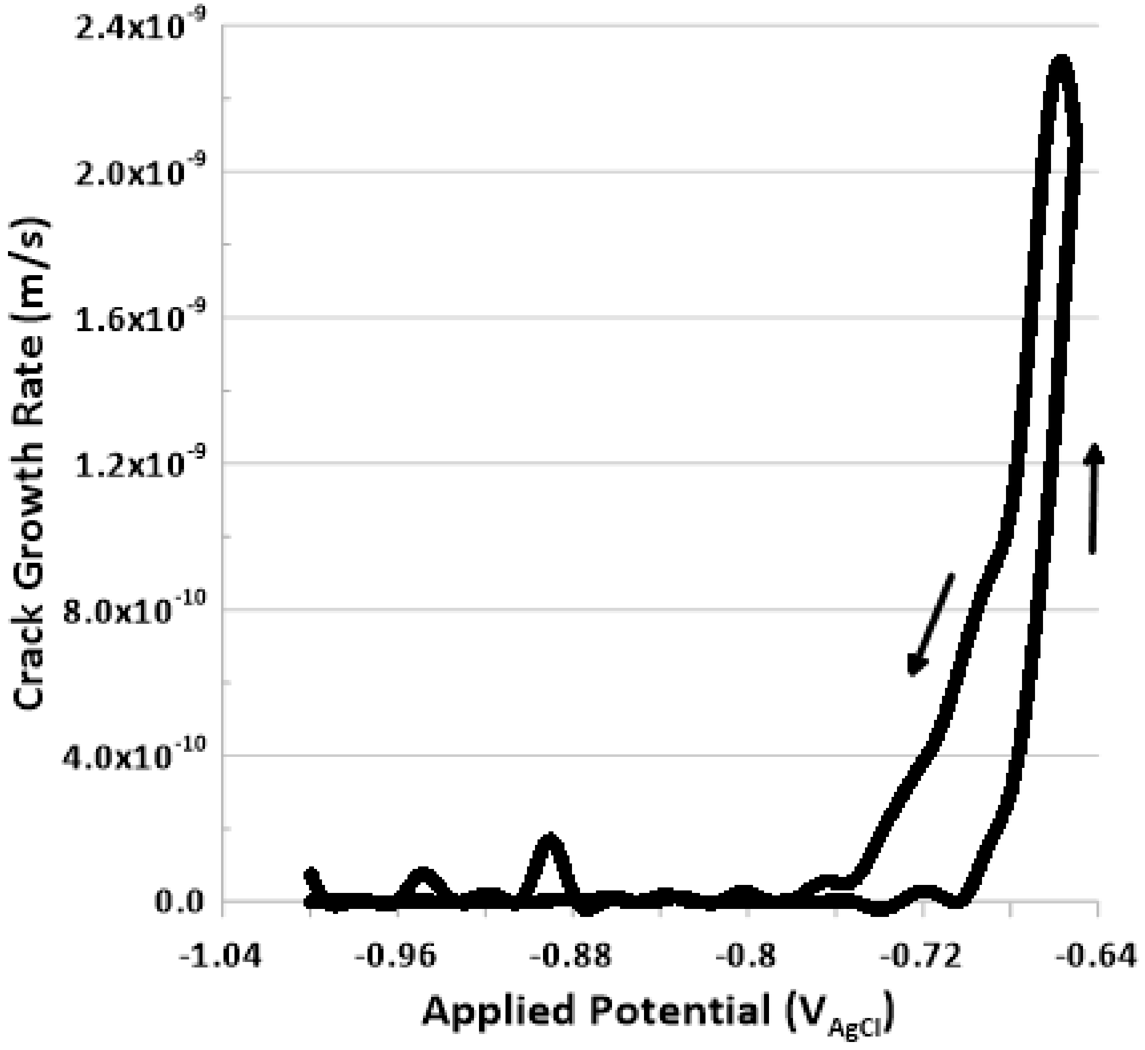


CGR increases by 2.5x – 5x upon drying

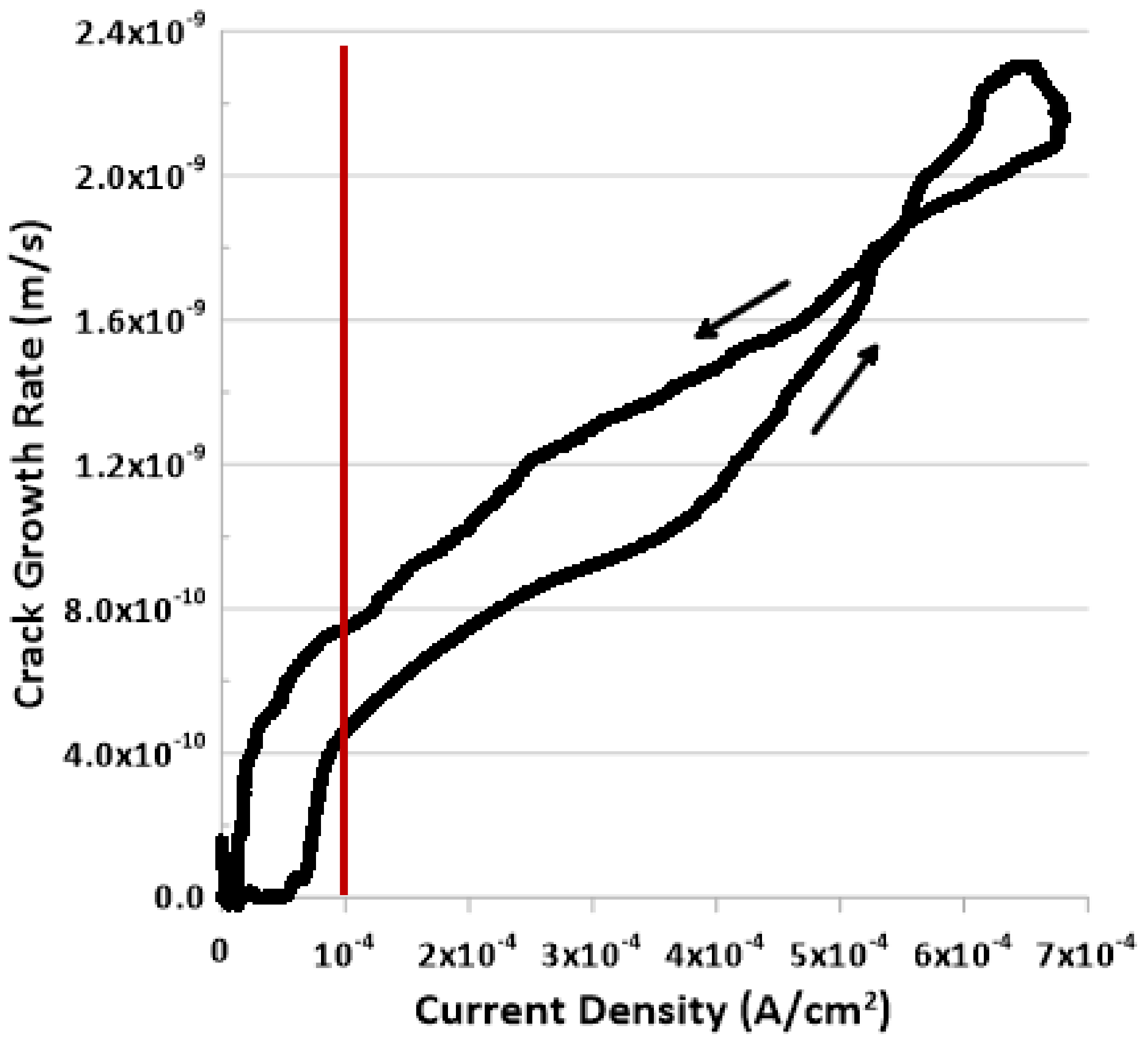
Under what conditions might we see SCC of AA7075-T6?

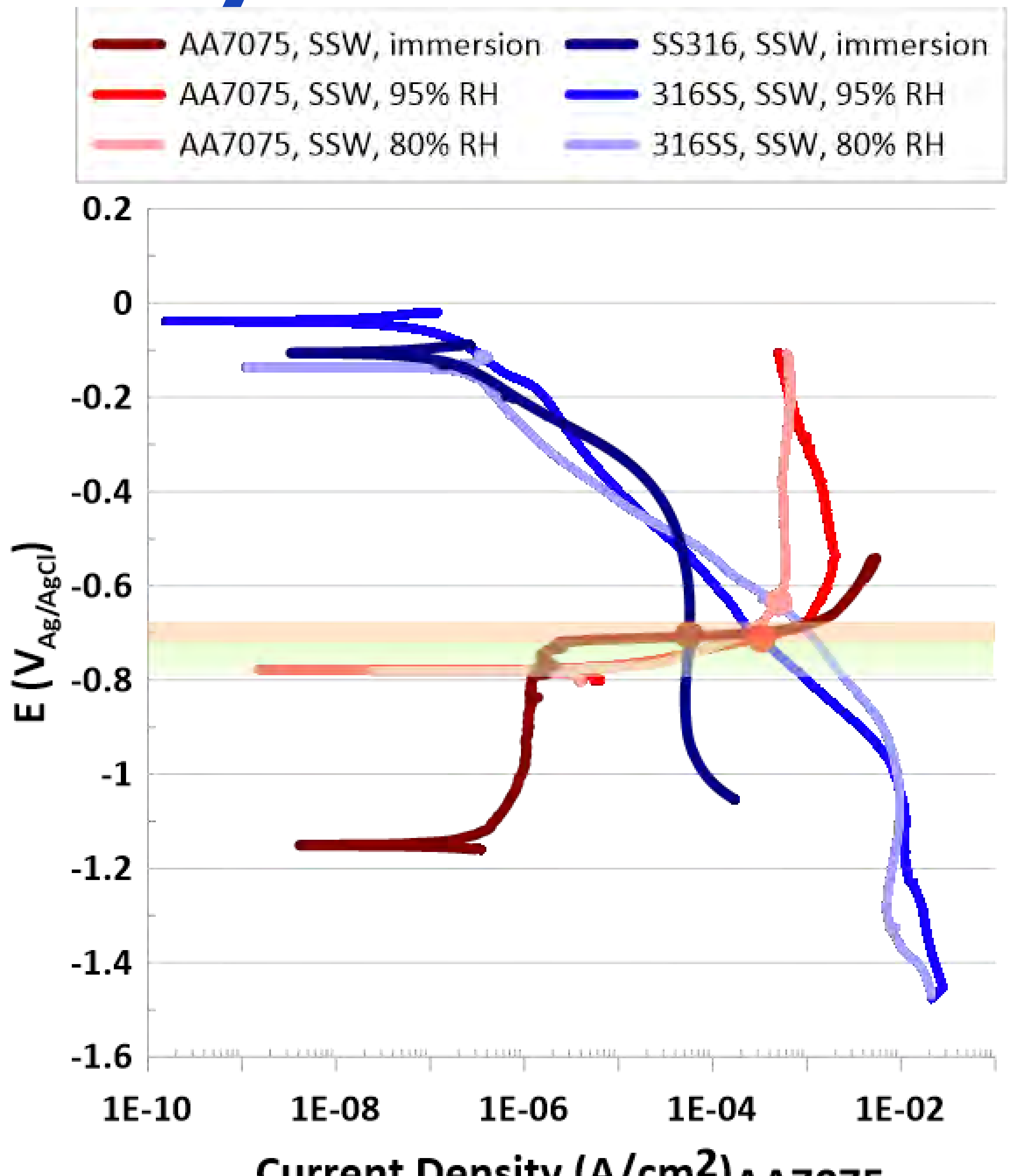
MATERIALS ENGINEERING

- Constant K from 0 to 16.49 MPa√m and immersed in deaerated sea water
- For K > 0, CGR initiates around -0.71 V (Ag/AgCl)
- CGR can continue to lower values but generally ceases as the potential falls below -0.75 V (Ag/AgCl)
- Implications
  - Cracking possibly initiated under aerated OCP conditions (OCP at the breakdown potential (E_{bd}))



Galvanic interactions likely increase CGR





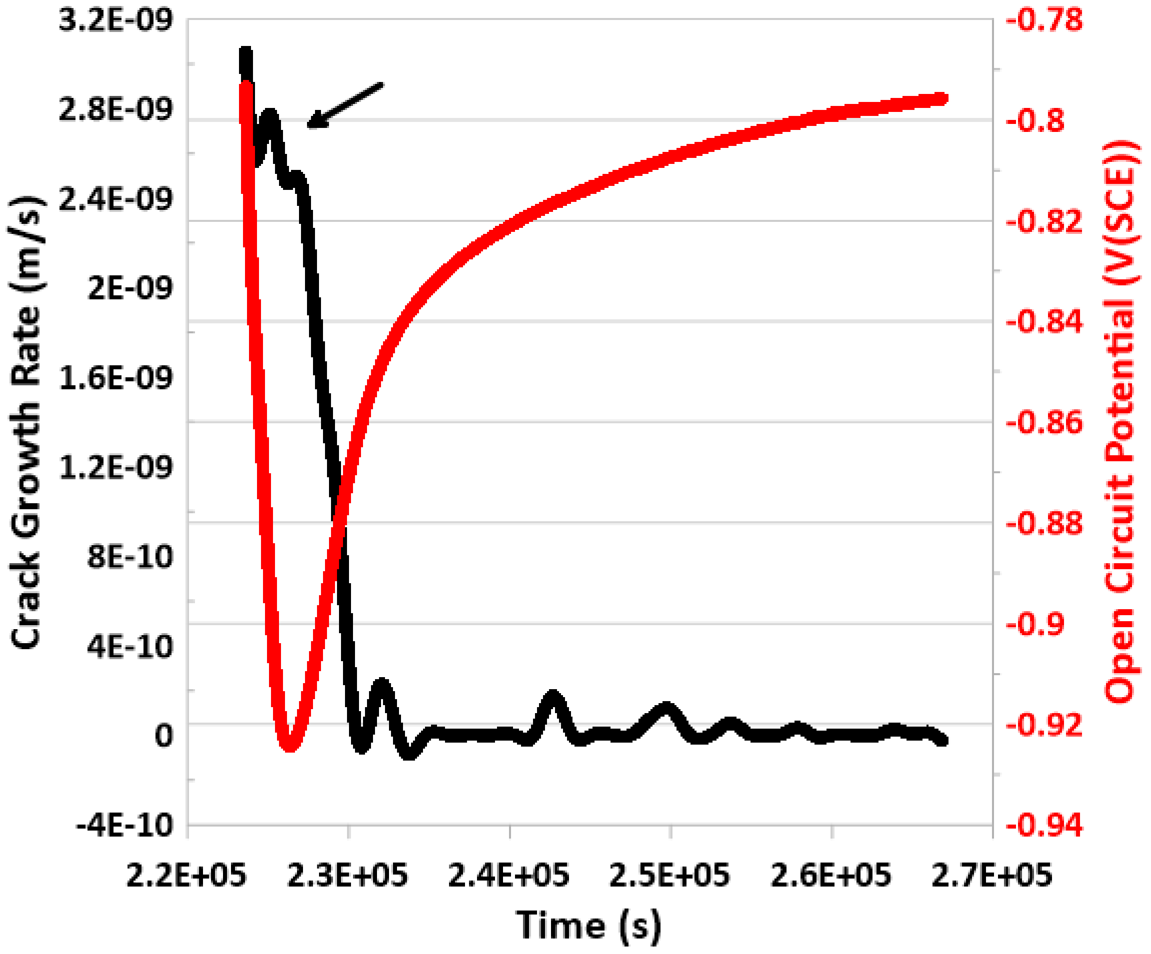
- Galvanic current drives CGR
- CGR = dissolution controlled

MATERIALS ENGINEERING

An aggressive crack tip chemistry can lead to sustained CGR well below -0.71 V(Ag/AgCl)

MATERIALS ENGINEERING

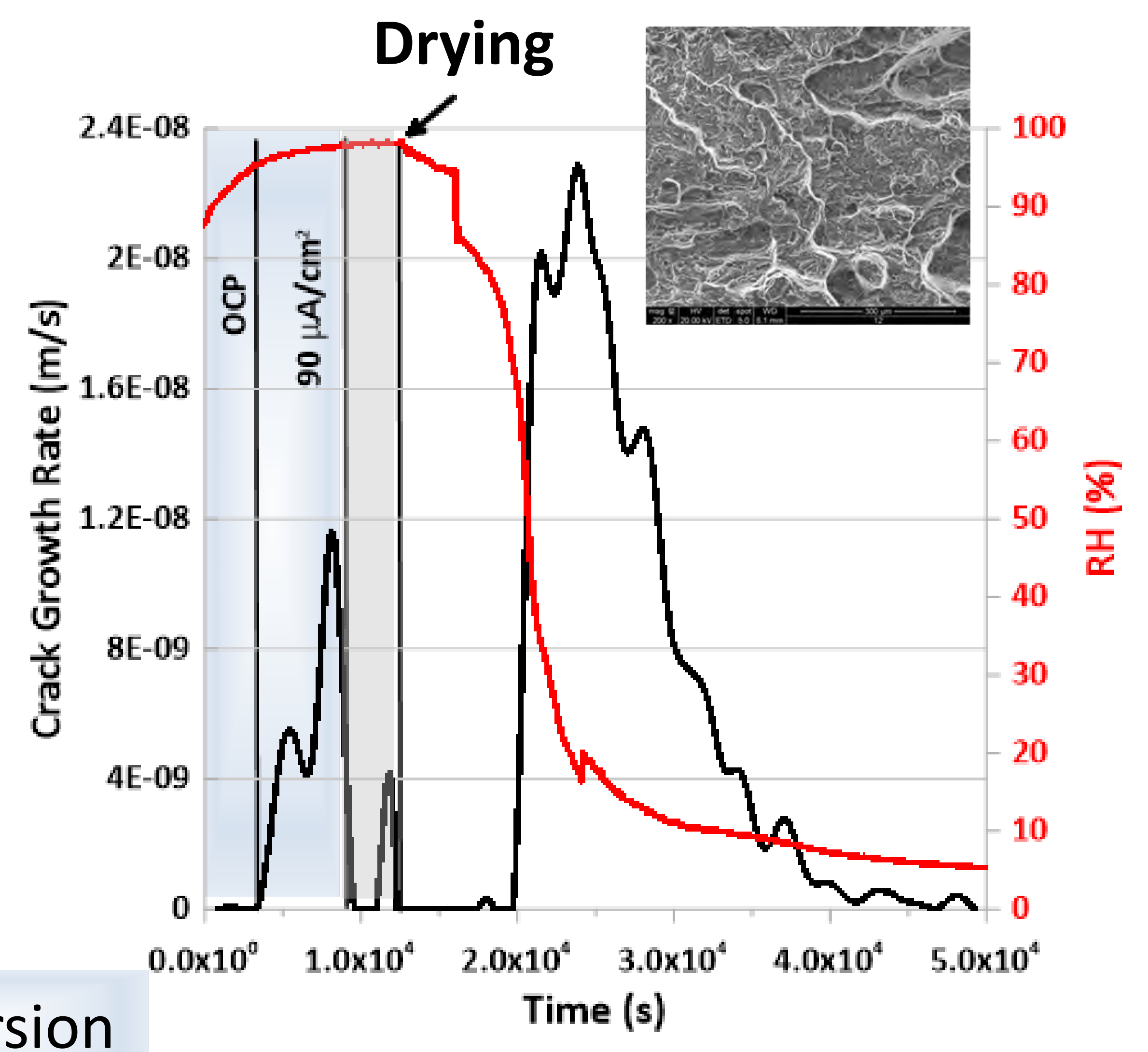
- Scan
  - Original OCP = -0.745 V(Ag/AgCl)
  - 12 cyclic scans of OCP to -0.65 V(Ag/AgCl)
  - Potential released to OCP
- OCP immediately falls to -0.92 V(Ag/AgCl), consistent with low pH values and high $AlCl_3$
- CG observed below critical potential range and until OCP begins to recover to initial value
- Implications
  - Cracking occurs until the environment at the crack tip is diluted by diffusion or exhauasted



Under atmospheric drying, the observed beavior is different than in solution.

MATERIALS ENGINEERING

- Cycle: Initiation at constant current density under immersion. Drain solution and maintain at 90% RH. Blow in dry lab air.
- As RH falls below 75% RH, large jump in CGR
- IG cracking observed with minimal corrosion
- Hypotheses
  - Increased H uptake relative to outward diffusion
  - Moisture dries from broad IGC sites but remains in GBs (very sharp crack)
  - Combo of both



Immersion

90% RH

What is SwRI doing?

MATERIALS ENGINEERING

- Working with ASIP community with interest in defining a test method
- Early goals
  - Can the cyclic exposure be used to compare SCC performance of AA7xxx alloys
    - Tighten up some experimental details
    - Optimize the cycle to highlight material performance differences
  - Expected funding starting Q2 FY25 to look at 3 to 4 alloys
    - 3 weapons platforms
    - In discussions with 1 OEM
- Mid-term goals
  - Using the developed cycle, move from alloy testing towards system testing, including protection systems and structural components

Fontana Corrosion Center
AT THE OHIO STATE UNIVERSITY

SAFE ENGINEERING

Environmental Effects 7xxx Series Aluminum Alloys

OSU: Jenifer Locke
SAFE: Sarah Galyon Dorman and Justin Rausch

The Ohio State University
COLLEGE OF ENGINEERING

Prior Work

- SAFE and OSU have worked together, separately and with various other partners on improving testing methods for EAC of 7xxx series aluminum alloys under atmospheric conditions to better predict this type of damage
  - Work under the Technical Corrosion Collaboration (FA7000-18-2-0001) examined effects of salt loading and other environmental effects on AA7085-T7451
  - This was leveraged by SAFE on work refining the developed environmental control system for this type of testing which has the ability to combine salt films, RH, salt spray, various background gases and temperature (FA7000-19-2-0026)
  - Work has highlighted to need to understand the drying cycle on the increased presence of environmental cracking on newer 7xxx series alloys

Chamber Design

Environmental variables include:

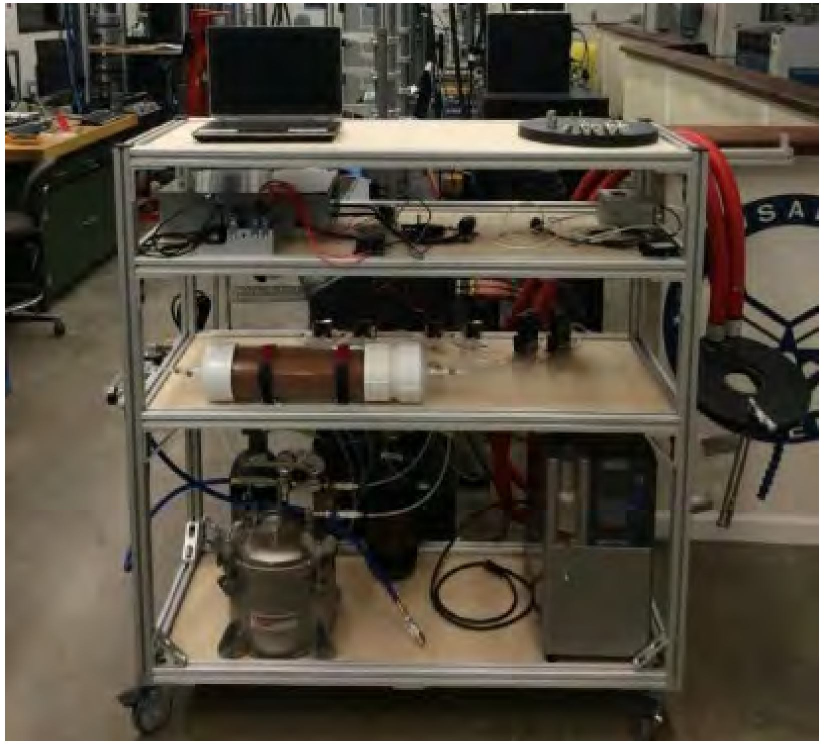
Relative Humidity
10%-100%

Ozone
30 ppb-100 ppm

Salt
10-1000 μg/cm^2

UV-light
UV-A

Temperature
-60-150 F



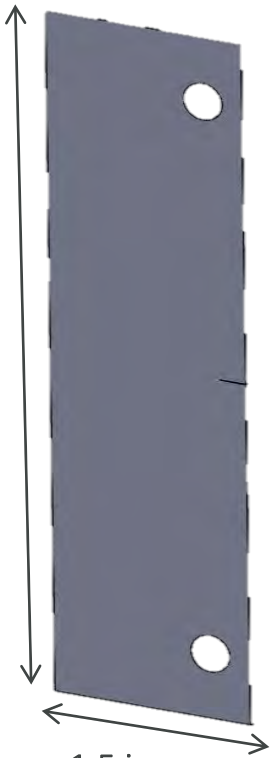
*Considerations for Laboratory Corrosion Fatigue Testing of Aluminum Alloys for DoD Applications. Galyon Dorman, Rausch, Niebuhr - 2023 DoD Corrosion Conference

Continued Refinement with Chamber Design

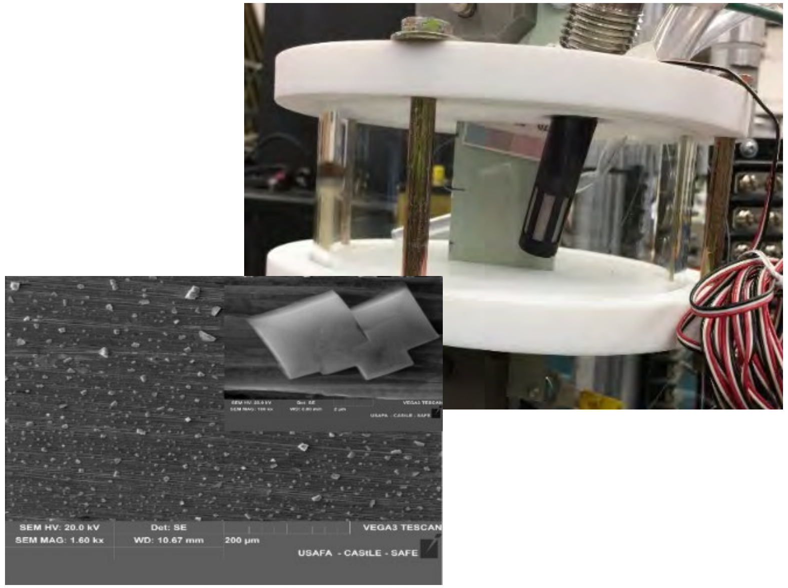
- Thin film for simulating atmospheric corrosion NaCl Solution of NaCl evaporated onto masked specimen
- Desire even dispersion of NaCl on sample surface
- Complex system requires refinement whenever a new environmental parameter is added
- Can be used on any sample design

AA7085-T7451

5.55 in

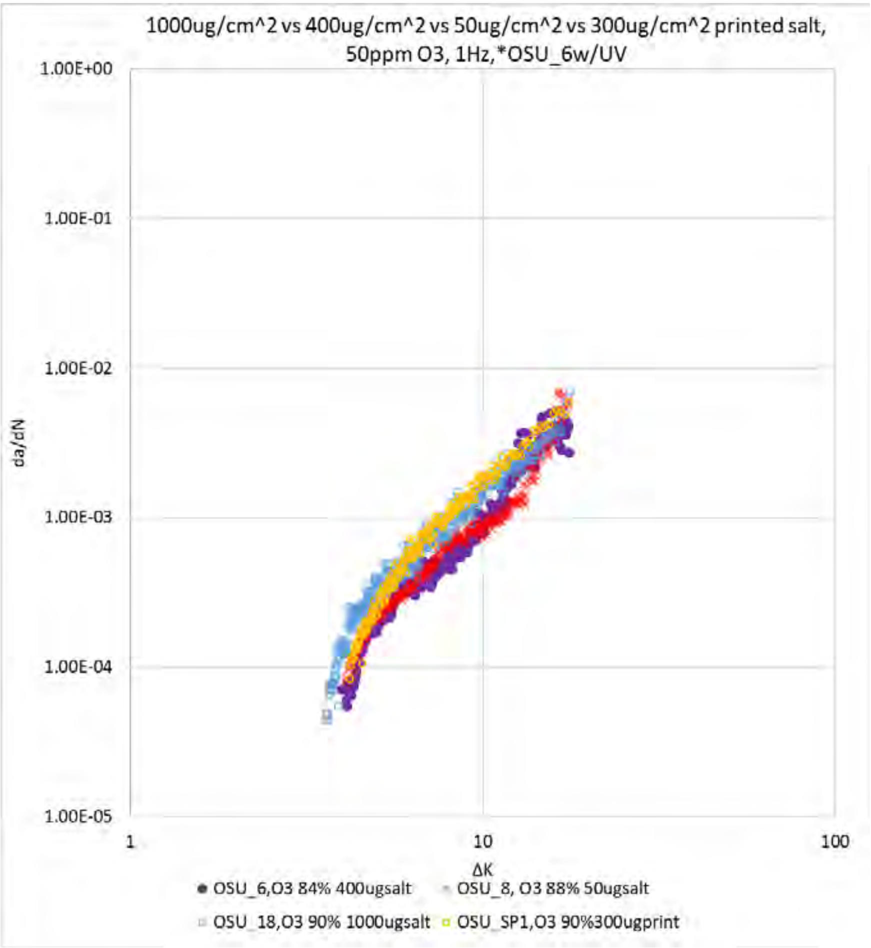


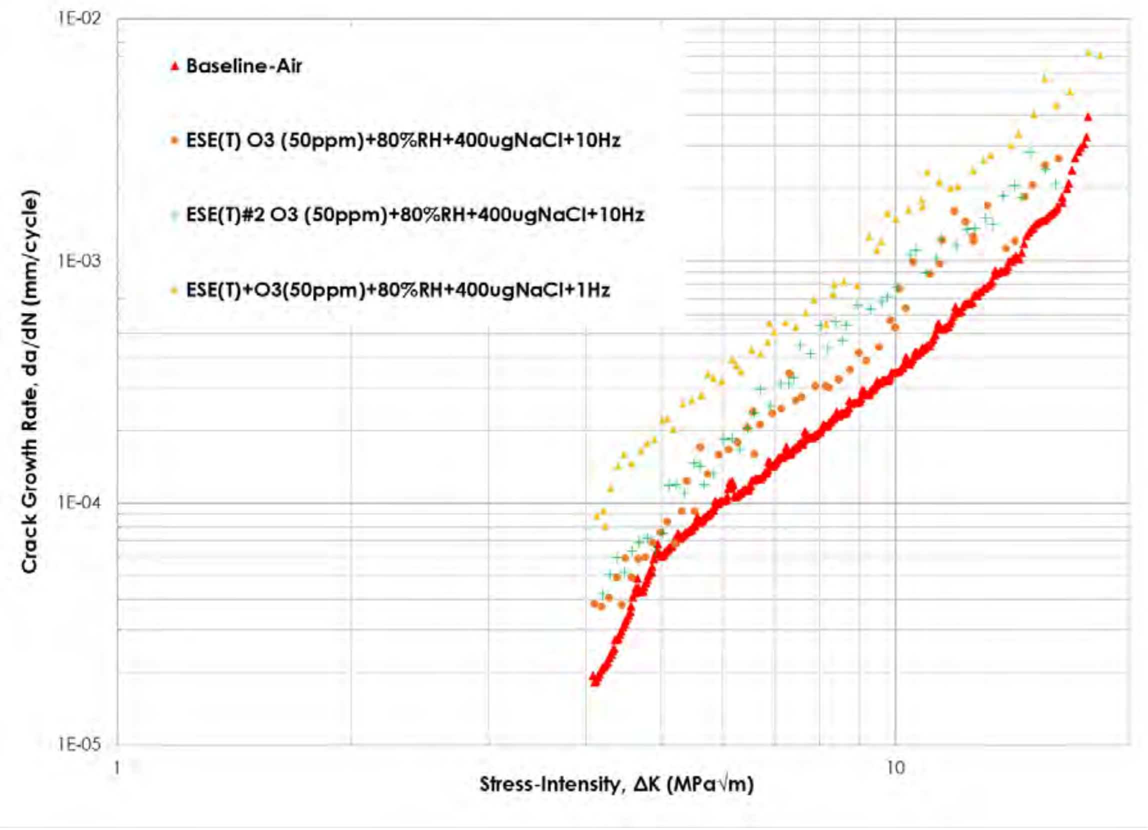
1.5 in



*Considerations for Laboratory Corrosion Fatigue Testing of Aluminum Alloys for DoD Applications. Galyon Dorman, Rausch, Niebuhr - 2023 DoD Corrosion Conference

Some variables aren't as impactful as others: O_3 and salt load density above ~100 μg/cm²

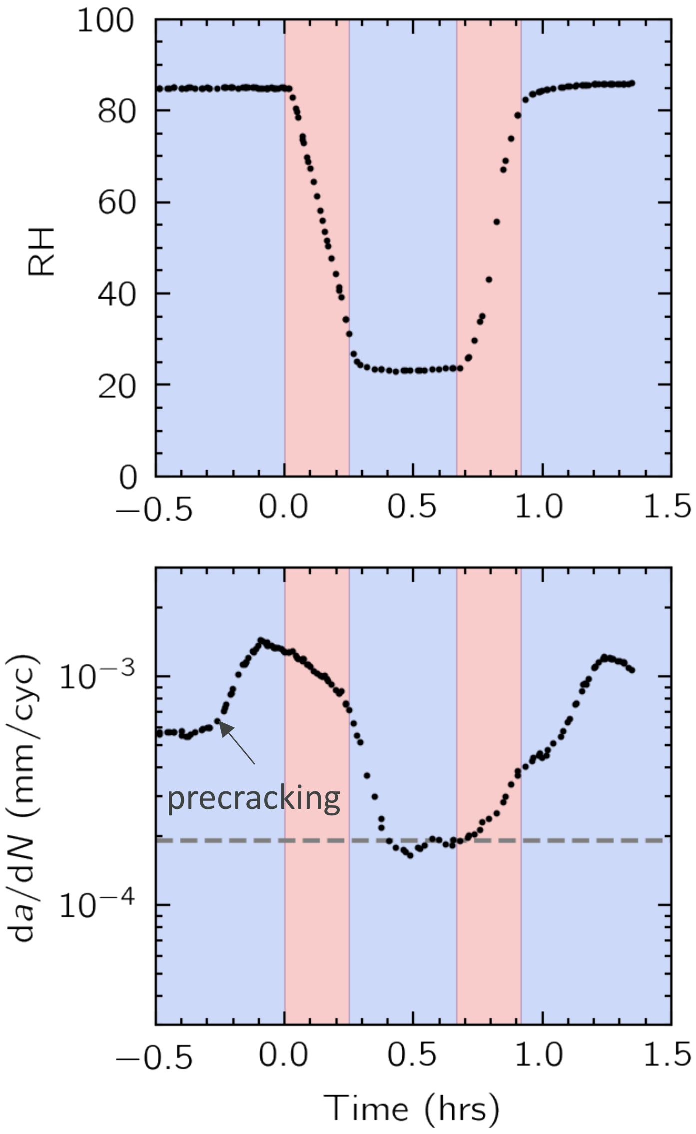




- The presence of ozone continues to have limited effect on the crack growth rates.
- Salt loading variation between 50-1000 μg/cm² does not appear to change crack growth rates.
- Salt films with lower concentrations of salt can be more suspectable to unexpected drying
- Currently there is limited difference noted between samples printed with salt and those with pipetted salt.

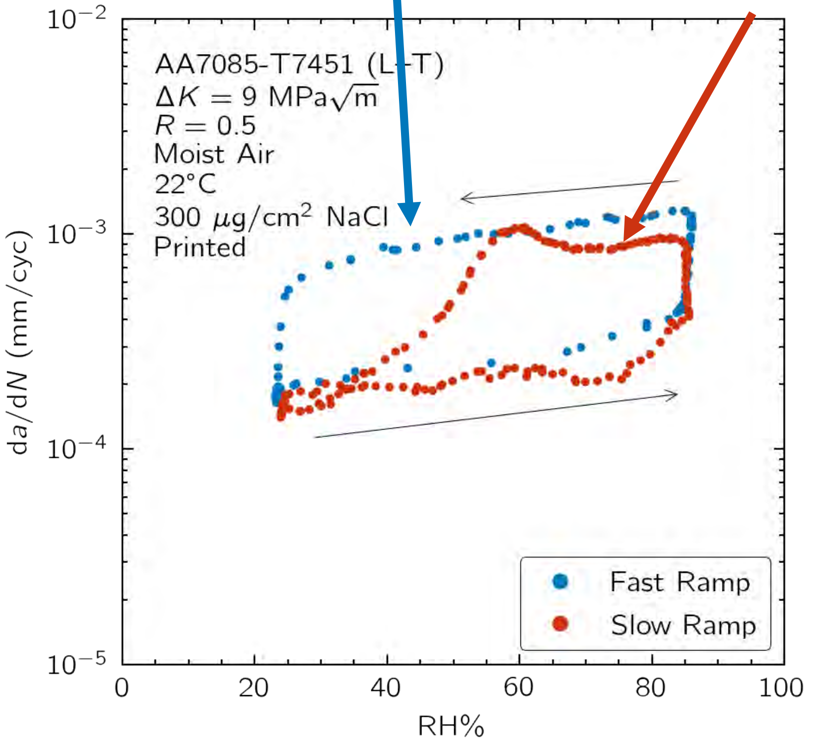
*Considerations for Laboratory Corrosion Fatigue Testing of Aluminum Alloys for DoD Applications. Galyon Dorman, Rausch, Niebuhr - 2023 DoD Corrosion Conference

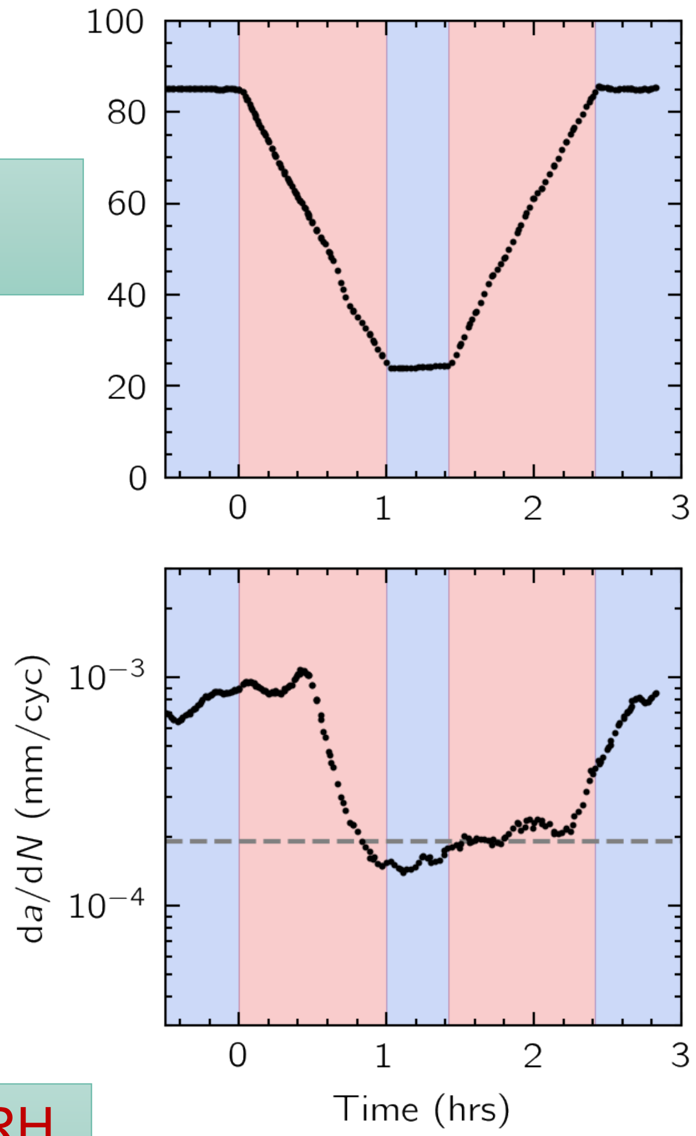
Crack growth rate during drying is dependent on drying rate



Ramp Time = 15 minutes
Hold Time = 25 minutes

Ramp Time = 60 minutes
Hold Time = 25 minutes

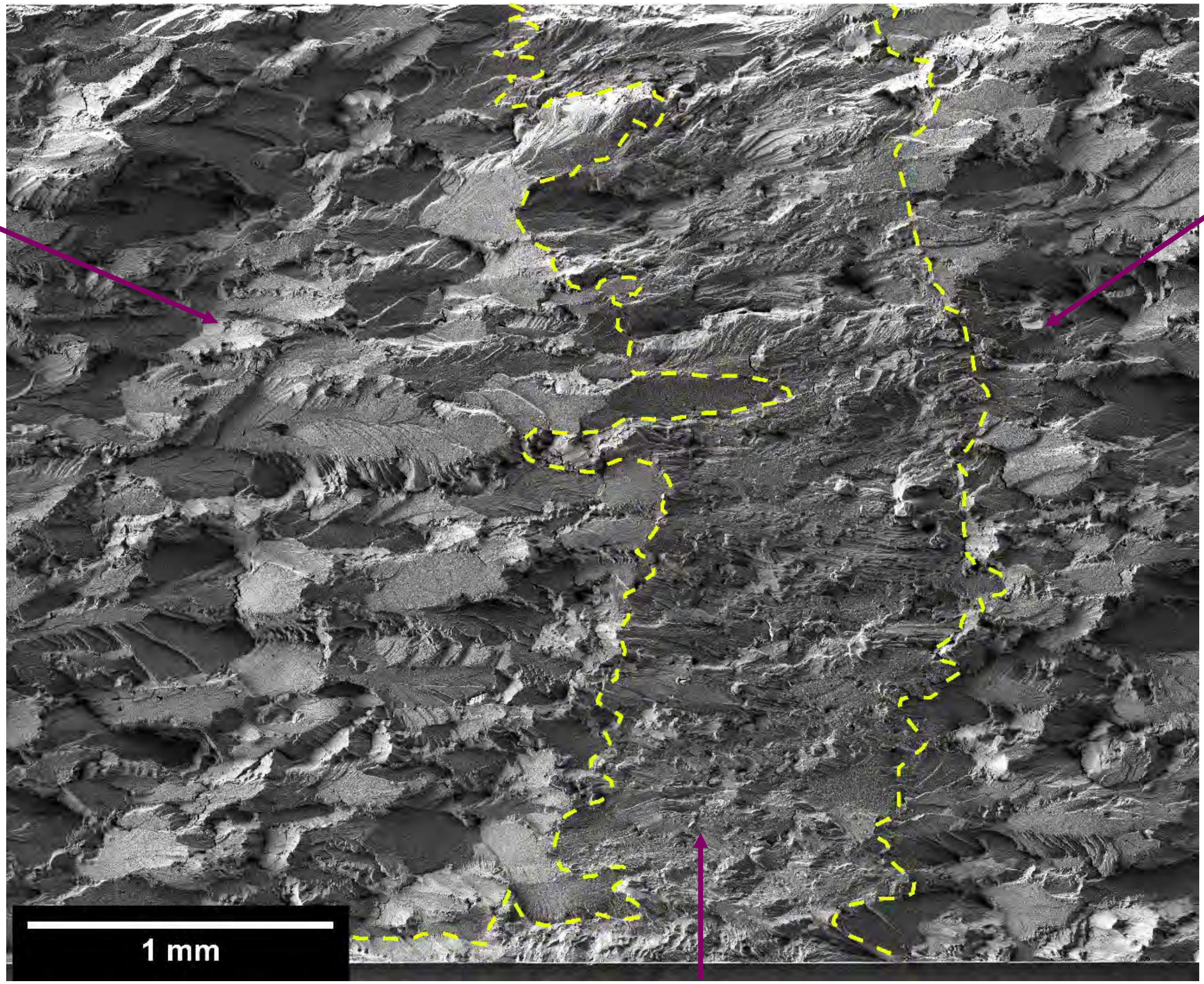




Cracking proceeds at high da/dN at lower RH when ramped more quickly

Fractography is consistent with previous findings of a transition from transgranular to intergranular cracking

High RH
High da/dN



High RH
High da/dN

Cracking Direction

Low RH
Low da/dN

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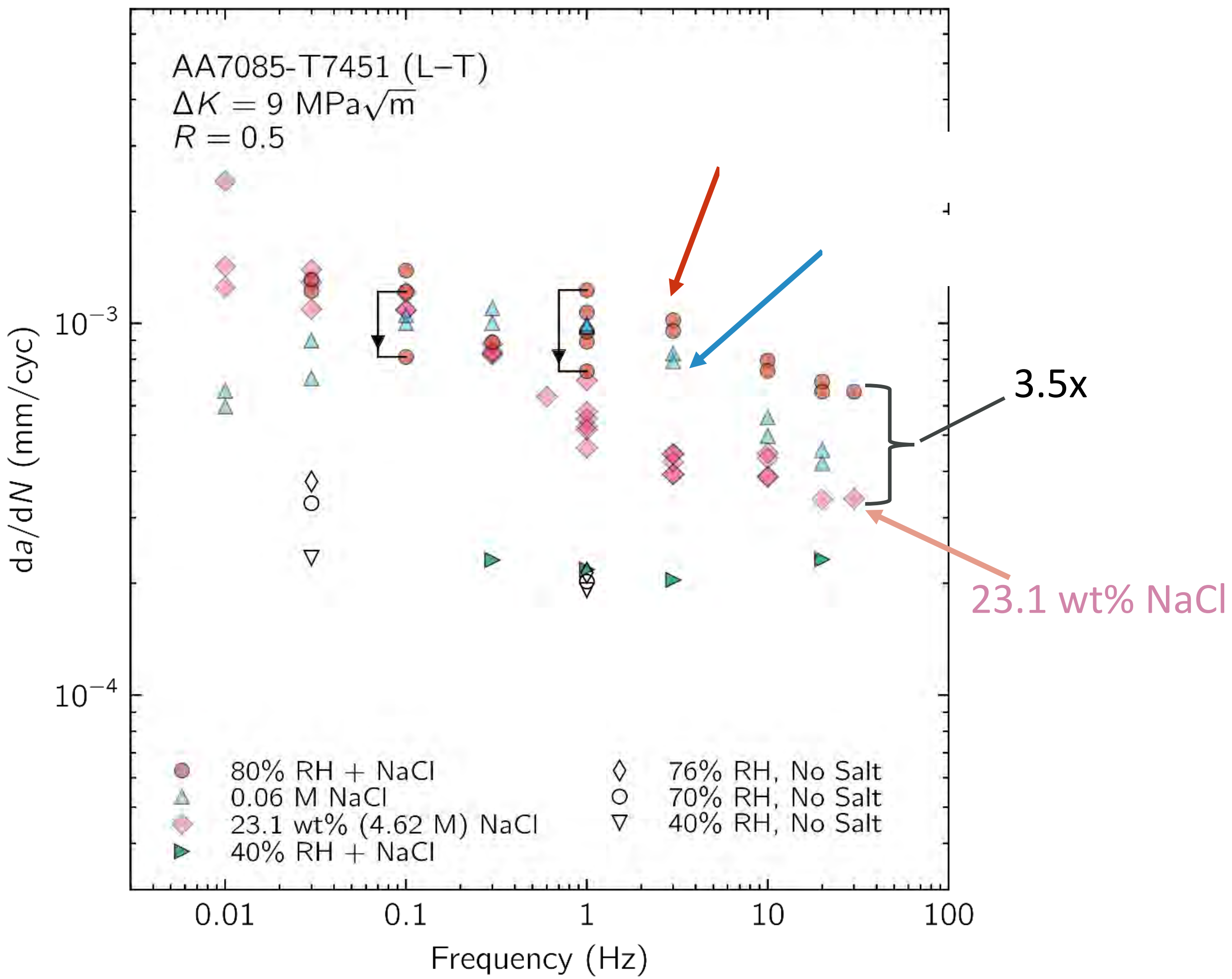
SAFE ENGINEERING

At low f (< ~1 Hz), all Cl^- containing environments have = da/dN
At higher f, atmospheric has accelerated da/dN



- 300 $\mu g/cm^2$ NaCl on surface and 80% RH ↑ da/dN over air with no salt
- 1 Hz and below, full immersion approximates atmospheric da/dN
- Above 1 Hz, atmospheric da/dN higher than similar salinity full immersion
- Approaching 10 Hz and higher, atmospheric da/dN is slightly higher than 0.06M NaCl
- conventional full immersion environments are suitable at lower f, but may underestimate at higher f

Free, Marino, Schindelholz, Dorman, Locke; International Journal of Fatigue, 167, 2023

A Current Program is Funded By ONR:

- Develop a Digital Twin to advance the state of the art for structural integrity modeling specifically with regards to corrosion and the transition to corrosion fatigue
  - Focus will be on AA7075-T6 for model development to ensure success, particularly with regards to large historical datasets available

1) Data mine and pull in data from other programs on corrosion and corrosion fatigue behavior as a function of atmospheric environmental variables (RH, T, O_3, UV, salt loading) to begin to build data driven Bayesian approach
2) Experimental examination of the effects of atmospheric environmental variables on corrosion fatigue crack growth rates on alloy itself where literature data are critically lacking
3) Perform sheltered outdoor tests to obtain validation data for digital twin
4) After initial creation, begin to incorporate the effect of bolts and coatings by on both corrosion and corrosion fatigue by integrating data from other similar work

A Current OSU Program Funded by NSF

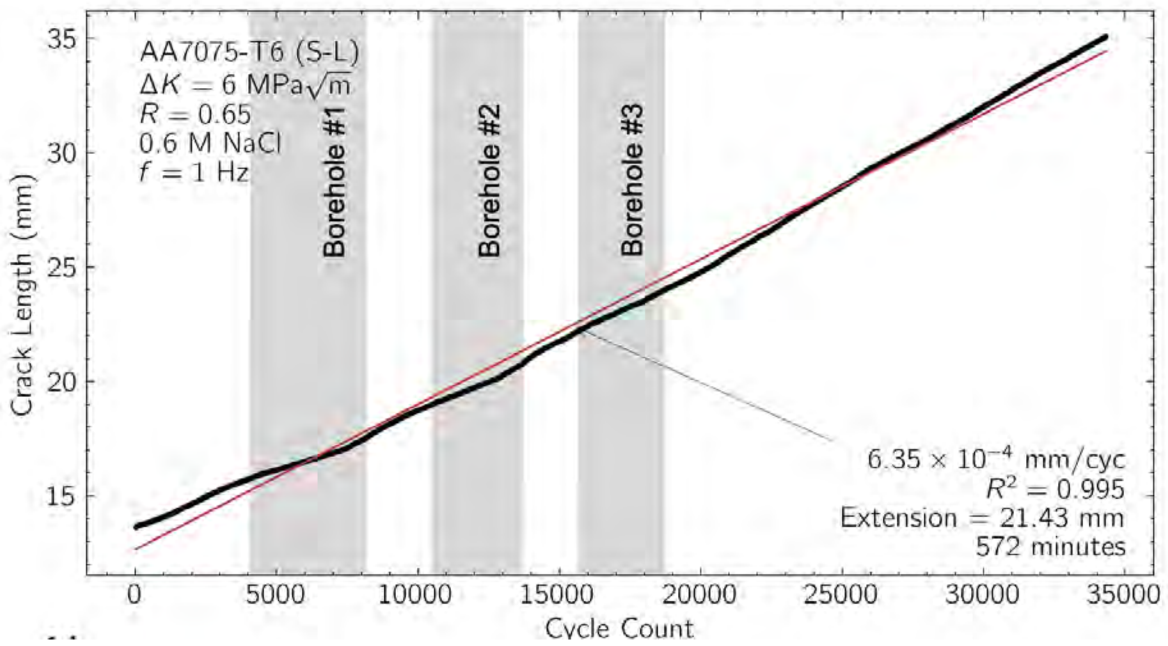
Hypothesis:

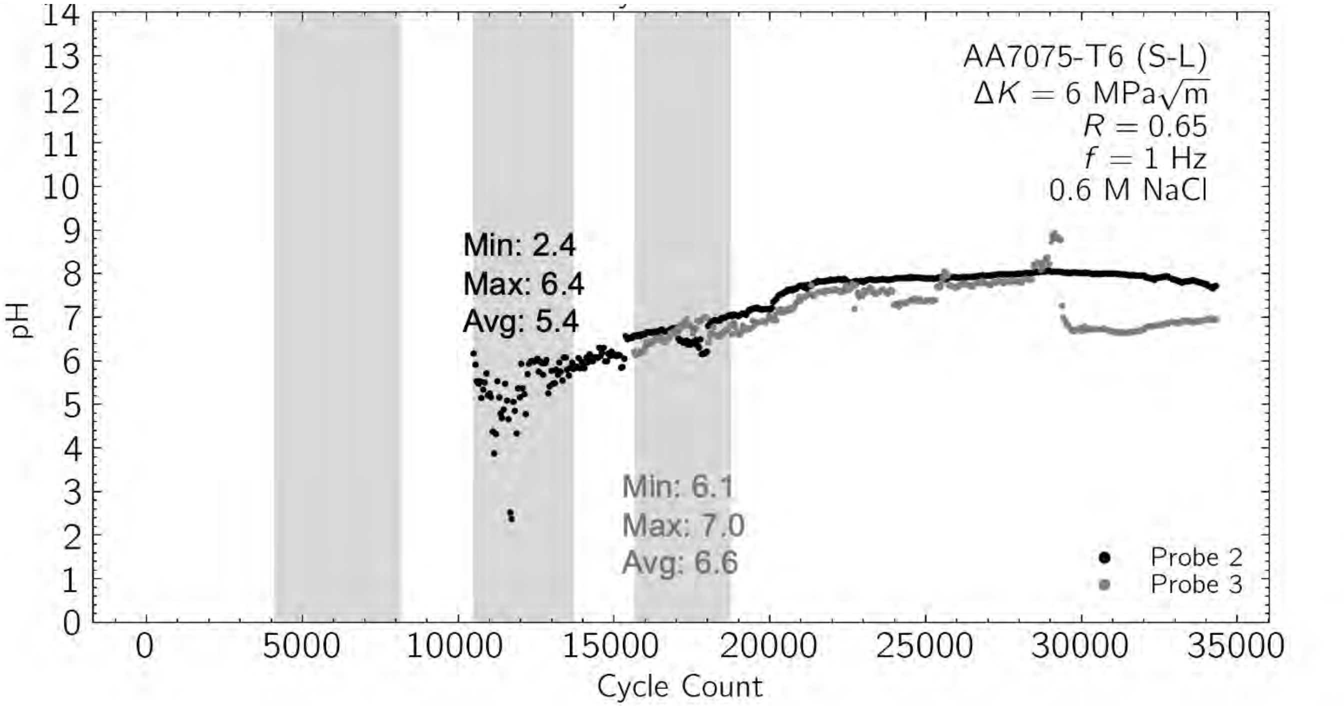
2xxx Al alloys have an intrinsic resistance to EAC compared to 7xxx alloys because Cu containing precipitates within the crack wake dealloy causing Cu to replate and accelerate cathodic reaction kinetics in the crack environment facilitating a more basic environment where a passive film can be stabilized

Objectives:

- Actively probe crack tip pH in 2xxx and 7xxx Al alloys to gain evidence in support of the fact that 2xxx have pH within range for Al passivity when da/dN is low
- Cast experimental compositions to varying the presence of dealloying/Cu replating precipitates
- Investigate effects of frequency on da/dN on experimental compositions
- Electrochemical characterization of compositions to determine propensity to passivate/repassivate

AA7075-T6 shows acidic crack under OCP





- 7075-T6 shows an acidic crack as low as 3.5 at 0.1 Hz
- @ 1 Hz mostly between 5.4 and 7

Montiel, Marino, Papageorge, Locke. Manuscript in progress.

Next Steps

- Confirming the conditions that consistently reproduce the damage in laboratory testing
  - Suspected wetting and drying conditions along with stress and temperature

- Determine the microstructure features that are driving the issue
- Develop a repeatable test methodology to screen for this issue in alloy development going forward
  - Consider that method may need to be somewhat flexible to allow for other unknown conditions of risk to be studied later if next generation alloys also show issues
- Because most of SAFE and OSU's work on this topic has been funded by governmental organizations the work should be sharable and available for validation.

BEASY
INNOVATIVE SOLUTIONS

AFRL-FAA TECHNICAL INTERCHANGE MEETING (TIM) ON ENVIRONMENTALLY ASSISTED CRACKING (EAC) / STRESS CORROSION CRACKING (SCC) OF HIGH-STRENGTH 7000 SERIES ALUMINUM ALLOYS

CMI BEASY SOFTWARE TOOL DEVELOPMENT & CAPABILITY OVERVIEW

5-6 NOVEMBER 2024

Company Overview

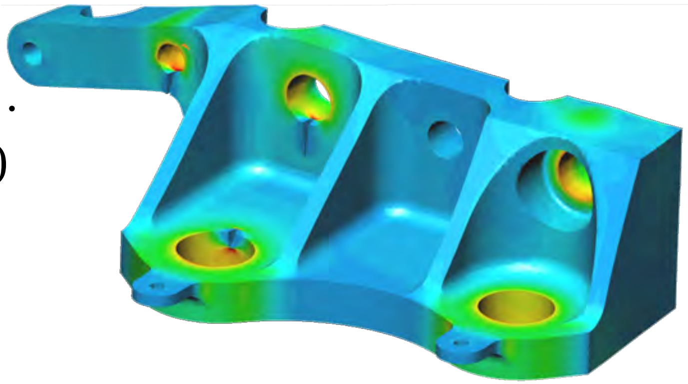
- Developer of advanced modeling and simulation tools for corrosion and fracture mechanics analysis
- Modeling services to support design requirements, asset management, and sustainment planning
- Extensive R&D work guides creation of client-driven, custom software solutions

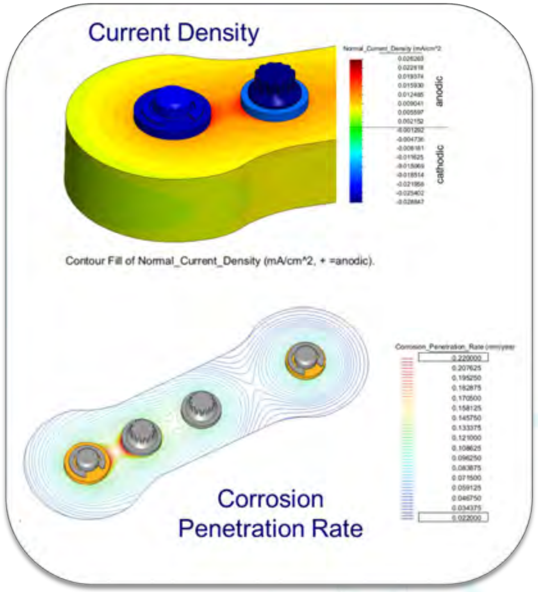
PROVIDING DURABILITY AND STRUCTURAL INTEGRITY SOLUTIONS WORLWIDE

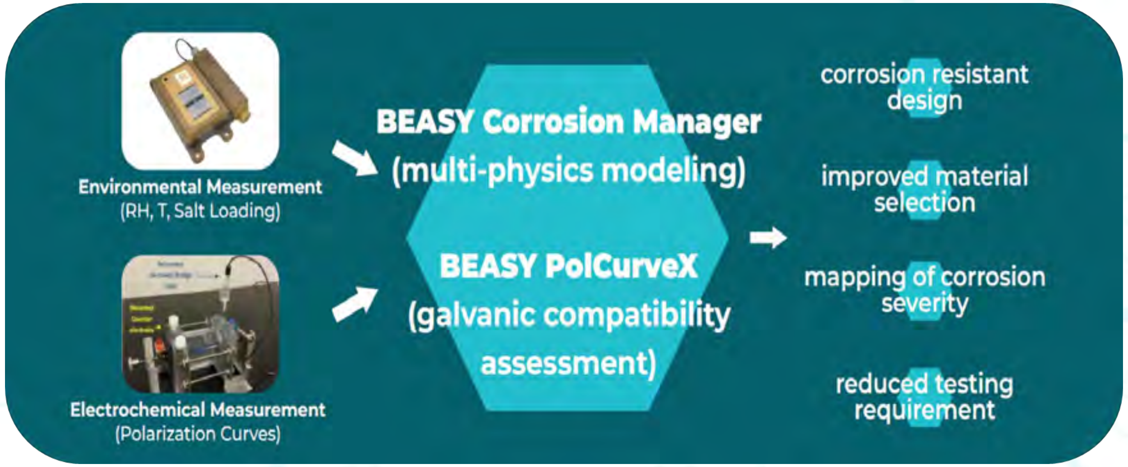
BEASY
INNOVATIVE SOLUTIONS

Corrosion & Fracture Mechanics Modeling Capability

- Fracture Mechanics:
  - BEM driven FCG simulations.
  - Automated remeshing and crack growth.
  - LEFM (residual stress, multi-site damage)
  - New advanced DDM solver
- Corrosion Manager:
  - FEA simulation package for galvanic corrosion for thin film and bulk electrolytes
  - Calculates IR drop through electrolyte for realistic component geometries.
- PolCurveX:
  - Materials database with tools for theoretical analysis of polarisation curves and de-convolution (MIL-STD-889).
  - 1d – curve crossing analysis
- Actively engaged in collaborations to expand and combine these into toolkits.





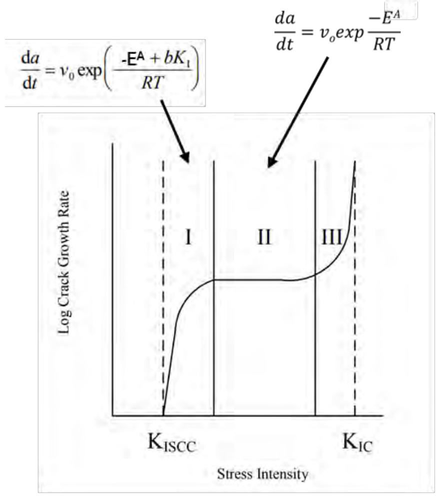


BEASY INNOVATIVE SOLUTIONS

Evolving EAC Modeling Framework

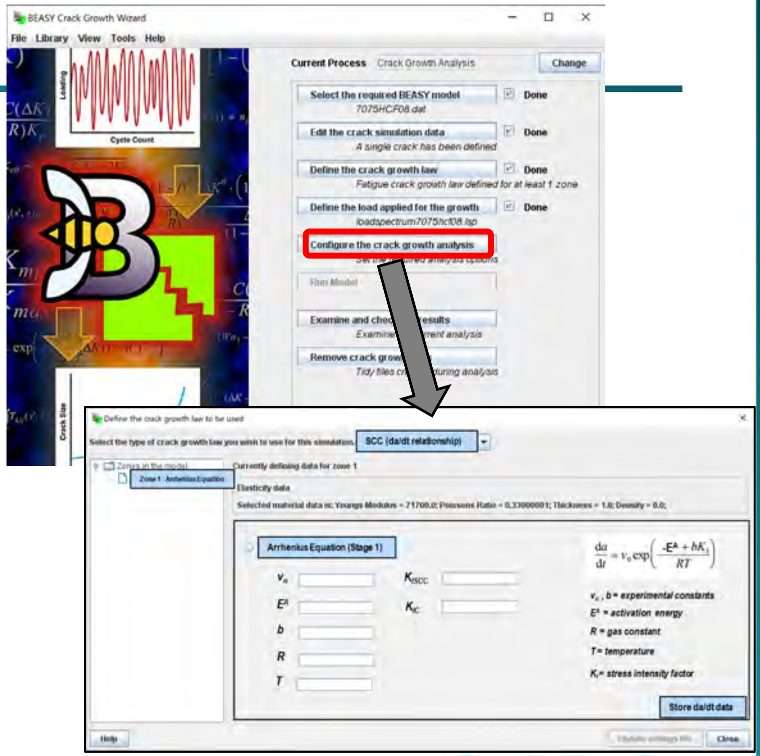
- **Proven simulation methodology supporting:**
  - Current density and potential distribution prediction for galvanic couples in both thin film and bulk electrolytes.
  - SIF solutions (mixed mode) for realistic models and crack surface geometry

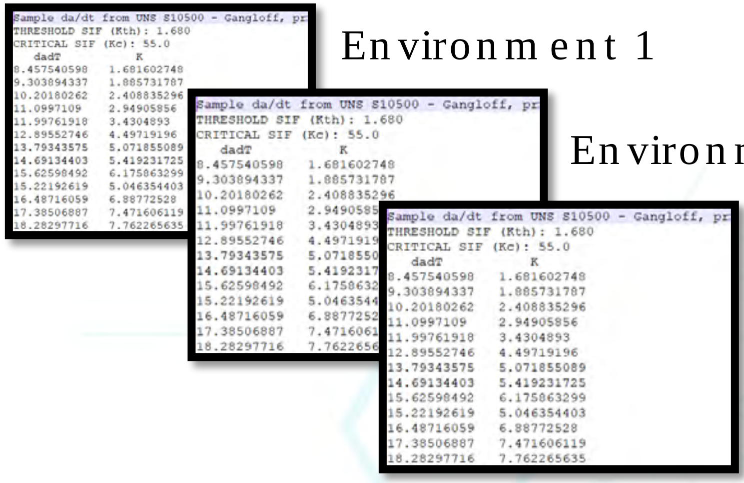
- **Capabilities include:**
  - Empirical crack growth rate equations
    - Arrhenius equation, *others to be included*
  - Tabular representation of crack growth rate as a function of environment and applied stress:
    - da/dt vs K data sets for different environmental conditions.



Stage I - K dependence

Stage II - Temperature and corrosive environment main driver, crack growth rate independent of K




Sample da/dt from UNS S10500 - Gangloff, pr
THRESHOLD SIF (Kth): 1.680
CRITICAL SIF (Kc): 55.0

dadT	K
8.457540598	1.681602748
9.303894337	1.885731787
10.20180262	2.408835296
11.0997109	2.94905856
11.99761918	3.4304893
12.89552746	4.49719196
13.79343575	5.071855089
14.69134403	5.419231725
15.62598492	6.175863299
15.22192619	5.046354403
16.48716059	6.88772528
17.38506887	7.471606119
18.28297716	7.762265635

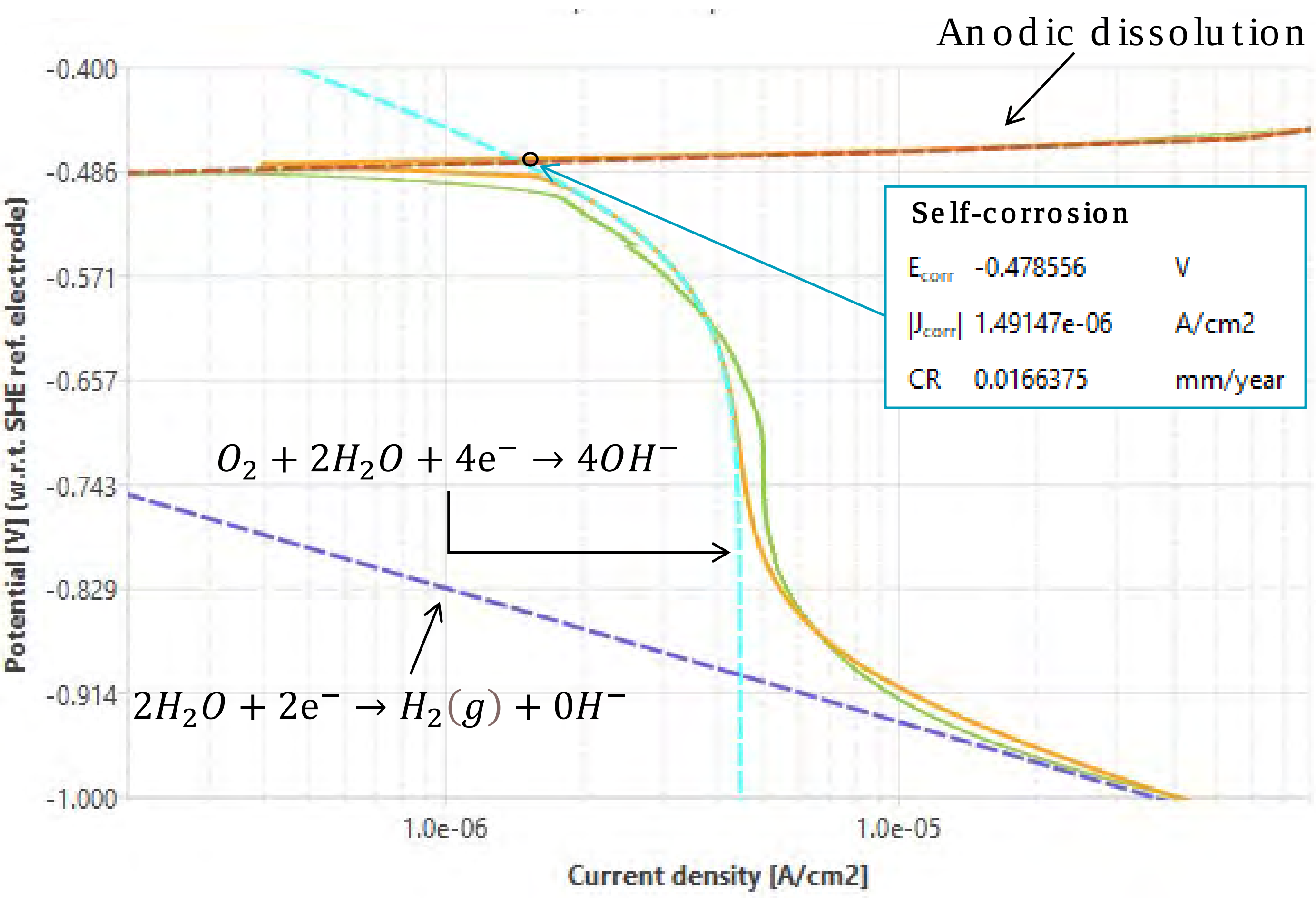
Environment 1

Environment 2

Environment 3

More realistic modeling of crack surface loading (conceptual)

Can we introduce H_2 charging effects ?



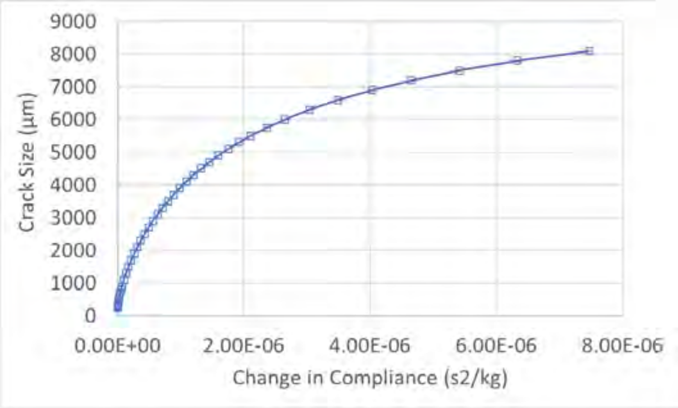
Hydrogen Evolution		
Sym.	Value	Unit
b_{H2}	0.11	V/decade
E_{H2}	-0.411	V
i_0^{H2}	1.62E-10	A/cm2
i_{lim}^{H2}	0.01122	A/cm2

b_k : Tafel slope, i.e. $b_k = 2.3RT/(\alpha nF)$
E_k : Equilibrium potential
i_0^k : Exchange current density
i_{LIM}^k : Limiting current density

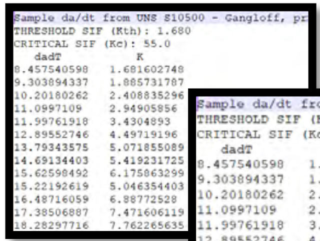
De-convolution analysis [MIL-STD-889]:
AA7075 in 3.5% NaCl electrolyte

Collaboration with Luna Labs - SCC Modeling

- Collaborative effort with Luna Labs to:
  - Assist in calibration of Luna's SLEAC measurement system (compliance based) by determining SIF solutions for range of crack sizes at given load



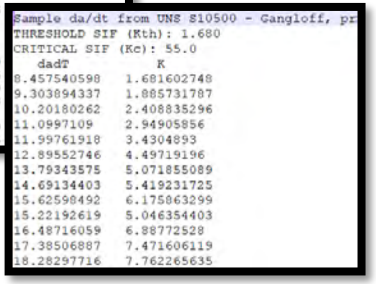
  - Integrate lab/field measured SCC crack growth rates into an environment-driven fracture mechanics framework that can be used as a predictive tool for realistic component geometry (ongoing)



Sample da/dt from UNS S10500 - Gangloff, pr
THRESHOLD SIF (Kth): 1.680
CRITICAL SIF (Kc): 55.0

dadT	K
8.457540598	1.681602748
9.303894337	1.885731787
10.20180262	2.408835296
11.0997109	2.94905856
11.99761918	3.4304893
12.89552746	4.49719196
13.79343575	5.071855089
14.69134403	5.419231725
15.62598492	6.175863299
15.22192619	5.046354403
16.48716059	6.88772528
17.38506887	7.471606119
18.28297716	7.762265635

Environment 1



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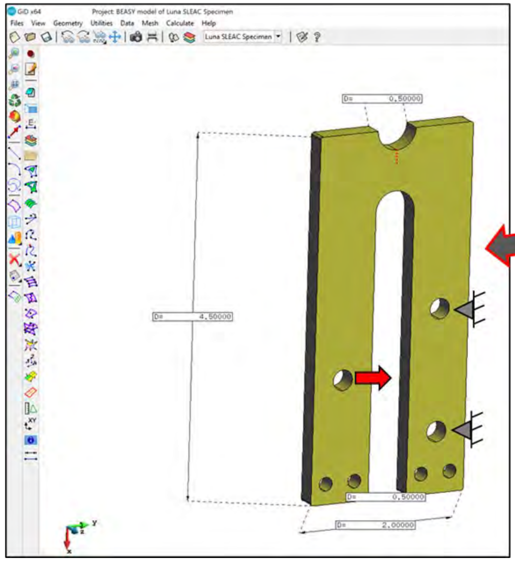
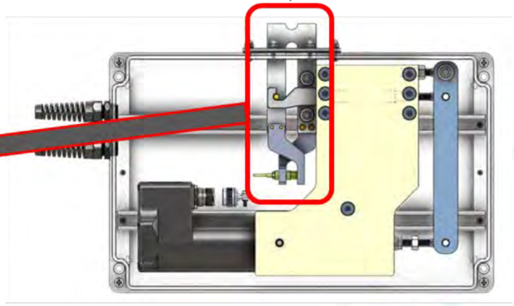
18.28297716	7.762265635

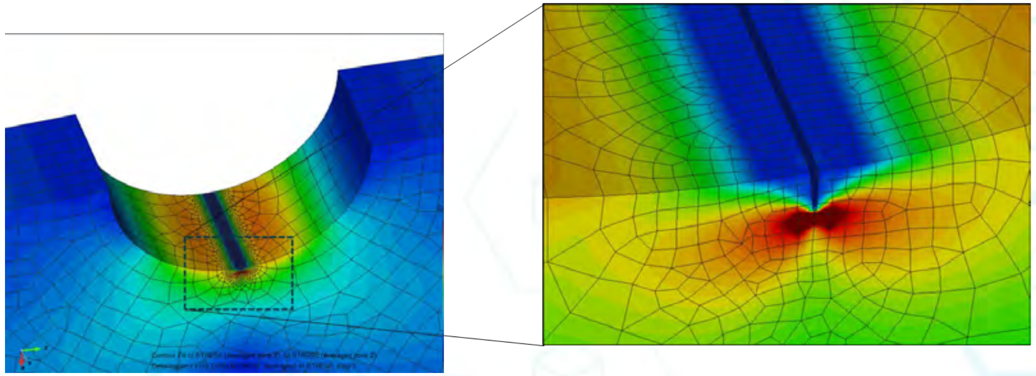
Environment 2

Double Cantilever Beam (DCB) is subject to sustained loading, under varying environmental conditions. A crevice former accelerates crack initiation in the notch area



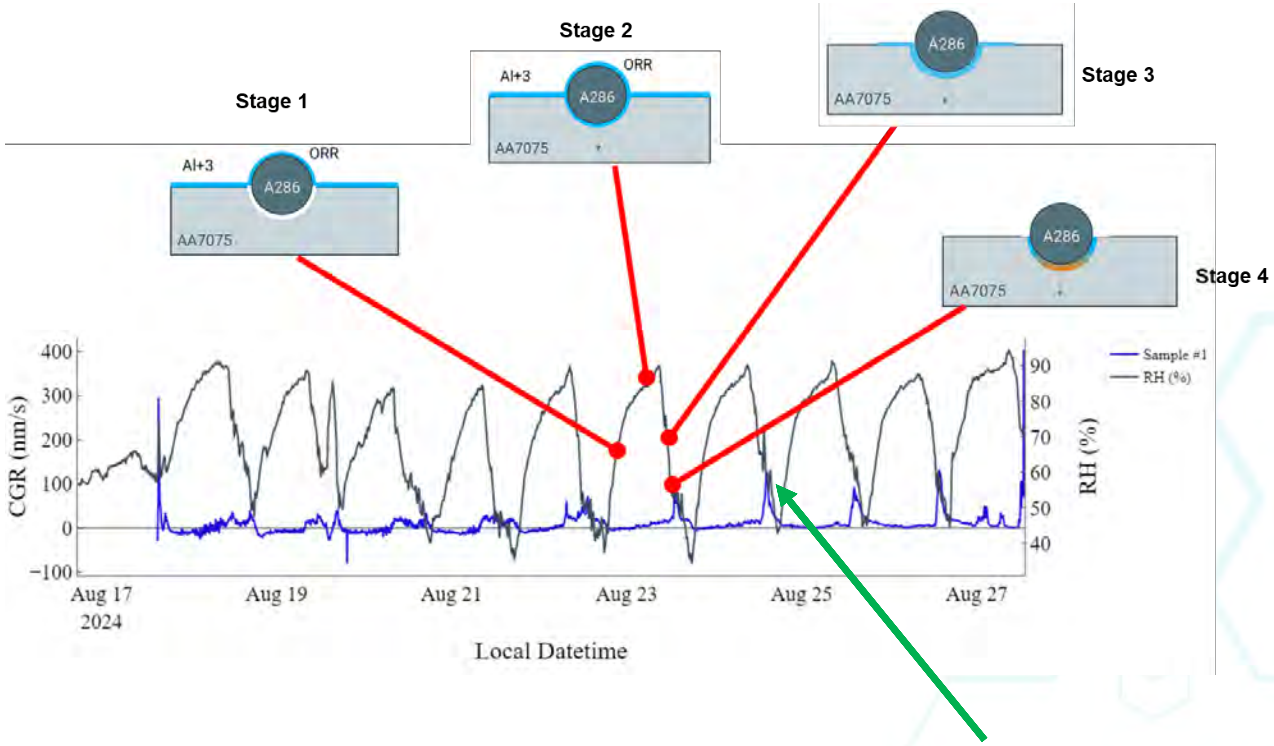
Luna SLEAC test article





Collaboration with Luna Labs - SCC Modeling

- Build atmospheric corrosion models for different stages of wetting/drying cycle (BEASY Corrosion Manager)
- Use BEASY Digital Twin methodology and Luna Acuity sensor dynamic measurement data to determine accurate model input parameters
- Investigate relationships between drying cycles and peak crack growth rates. Develop methodology to incorporate in a EAC modelling framework for different operational environments (ongoing)



Cracking and peak crack growth rates found to occur on the drying cycle

How could the modeling community interact ?

- Leverage knowledge to improve/expand modeling methodology (e.g. empirical SCC equations specific for 7XXX series alloys)
- Leverage new test data to populate and drive models. Access representative input parameters (e.g. E_A, K_{Iscc}, da/dN for in-solution environments)
- Academic research that may improve development of computational methods (e.g. consider H_2 charging or dissolution mechanisms in crack advancement algorithms)
- Continue to iterate and build out new capability based on feedback from EAC research community with a goal of having engineering level tools that can be used in practice

BEASY INNOVATIVE SOLUTIONS

THANK YOU

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