Hydrogen compatibility of aluminum alloys for fuel cell vehicle applications

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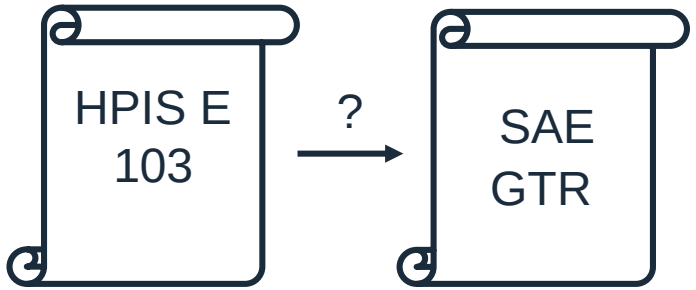
Background

Need for a qualification method of aluminum alloys for usage in hydrogen gas environment

Proposed
japanese standard



Proposal (derived from ISO 7866*):
Stress corrosion cracking (scc) test in humid air

- 25 °C ± 5
- > 85 % rh (no dew)
- 90 days

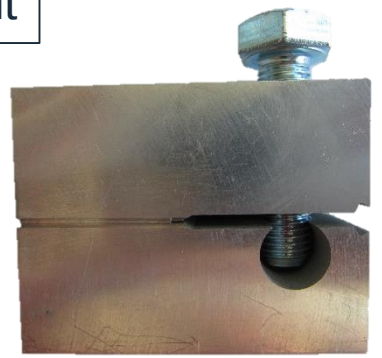
- Either constant load
- or constant displacement condition

Project aim:
Practicability of the proposed test method?

Project parameter:
- 20°C + 85 %rh
- 30°C + 85 %rh
- 20°C + 100 %rh
- 30°C + 100 %rh

constant displacement

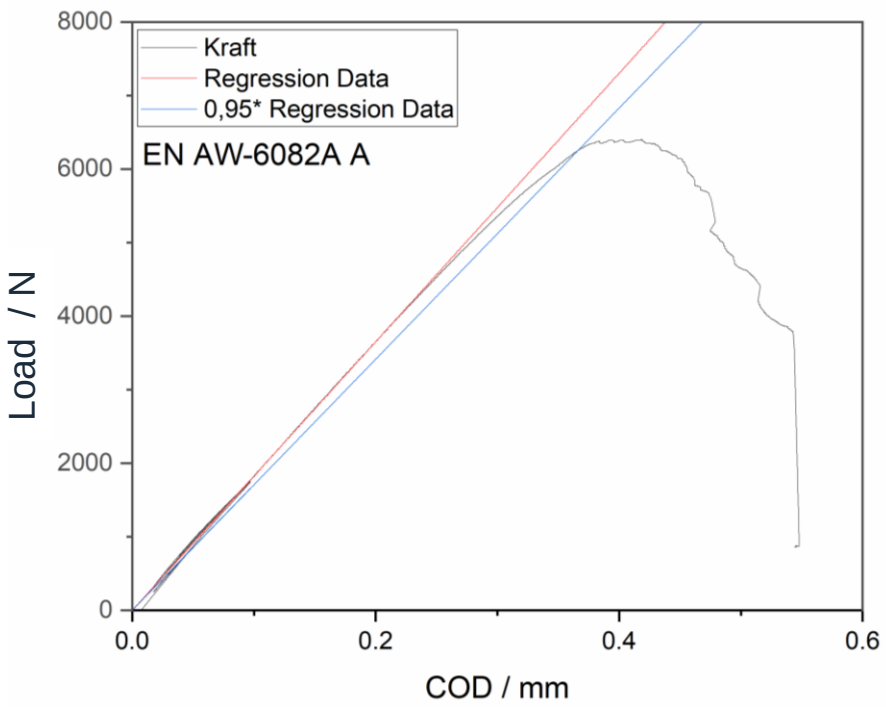
Industry members chose **two 6082** variants out of multiple proposed aluminum alloys.
(6061, 6110, 5042, 7075)



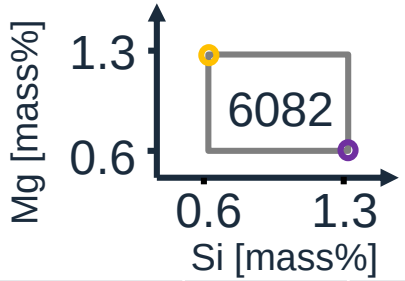
*Gas cylinders – Refillable seamless aluminum alloy gas cylinders; Design, construction and testing

Aluminum Alloys EN AW-6082A

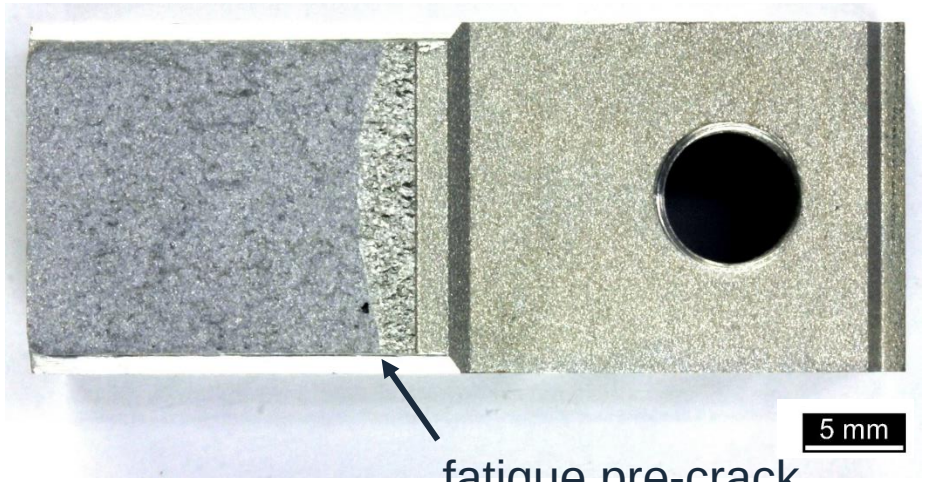
[wt%]	Mg	Si	Mn	Cu	Cr	Fe	Zn	Ti	Pb
6082A A	1.2	0.7	0.5	0.02	0.02	0.41	0.14	0.03	0.002
6082A B	0.6	1.3	0.02	0.01	0.02	0.42	0.14	0.03	0.002



→ K_{Ic} = 18.8 MPam$^{1/2}$



	Ys [MPa]	UTS [MPa]
6082A A	203	271
6082A B	310	338



Parameters (according to japanese Standard HPIS E 103):

	6082A A	6082A B
Stress intensity factor K_{IAPP} (0.056*Rp0.2)	11.4 MPam$^{1/2}$	17.4 MPam$^{1/2}$

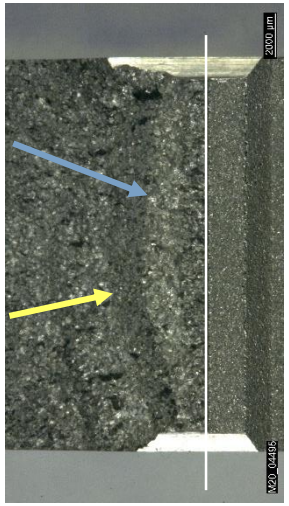
SCC Test results

exposure via climate chamber

Case	Crack propagation	K_{IA} versus K_{IAPP}	Judge
I	$(a_{scc}-a_{pre}) \leq 0.16$ mm	$K_{IA} < K_{IAPP}$	invalid
II		$K_{IA} \geq K_{IAPP}$	pass
III	$(a_{scc}-a_{pre}) > 0.16$ mm	$K_{IA} \leq K_{IAPP}$	fail
IV		$K_{IA} > K_{IAPP}$	invalid

fatigue pre-crack

SCC crack



	Material	Crack extension Δa [mm]	K_{IA} [MPam$^{1/2}$]	K_{IAPP} [MPam$^{1/2}$]	Result
A	30°C + 100 %rh	0	11.3	11.4	pass
	30°C + 85 %rh	0	11.3	11.4	pass
	20°C + 98 %rh	0	10.9	11.4	pass
	20°C + 85 %rh	0	10.5	11.4	invalid
B	30°C + 100 %rh	1.3	16.7	17.4	fail
	30°C + 85 %rh	1.3	16.7	17.4	fail
	20°C + 98 %rh	1.6	16.6	17.4	fail
	20°C + 85 %rh	0.34	13.0	17.4	fail

→ Consistent/ conservative SCC test results by varying the test parameters within the allowed range

SCC Test results

exposure via climate chamber

Case	Crack propagation	K_{IA} versus K_{IAPP}	Judge
I	$(a_{scc}-a_{pre}) \leq 0.16$ mm	$K_{IA} < K_{IAPP}$	invalid
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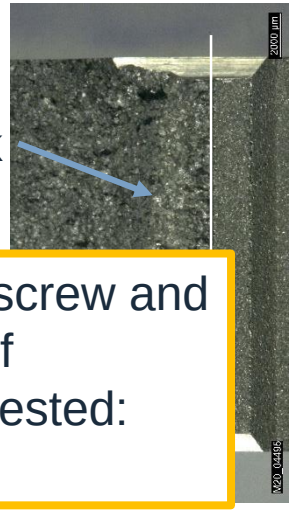
IV		$K_{IA} > K_{IAPP}$	invalid

fatigue pre-crack



due to friction of the screw and settling →definition of threshold value suggested: e.g. $0.95*K_{IAPP}$

	Material	Crack extension Δa [mm]	K_{IA} [MPam$^{1/2}$]	K_{IAPP} [M	
A	30°C + 100 %rh	0	11.3	11.4	pass
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	20°C + 98 %rh	0	10.9	11.4	pass
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	20°C + 85 %rh	0.34	13.0	17.4	fail

→ Consistent/ conservative SCC test results by varying the test parameters within the allowed range

Summary

❖ 6082A-A passed and 6082A-B failed the proposed test in all examined environments. In one condition the test was invalid. The range of test parameters give consistent results.

- The applied load/stress intensity factor is based on the yield strength.
- Generally, an increasing stress intensity factor leads to a decreasing yield strength.

- No destinction between linear-elastic and elastic-plastic material behavior

- The existence and the consequence of a critical stress intensity factor is not taken into account. (according to the proposed standard loading the specimen to a value greater than the critical stress intensity factor is possible but would defeat the purpose of the scc test)

- Questionable if the material behavior in humid air is the same as in hydrogen gas environment. (not covered in this project)

Questions.!?

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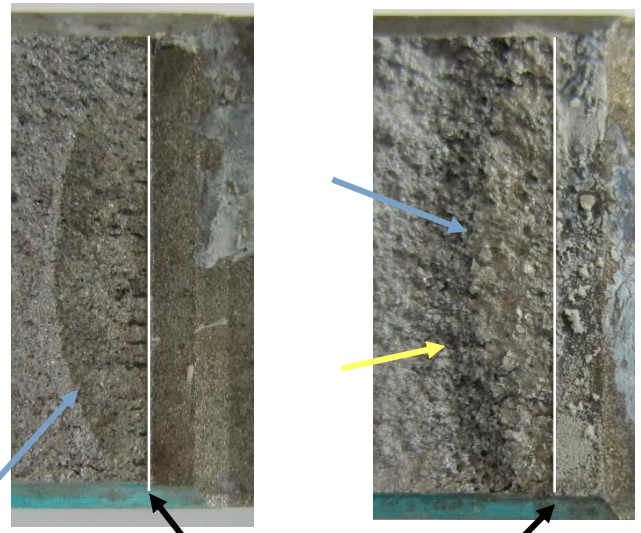
Department Operational Behavior under Medium Influence

1. 30°C + 100 %rh

6082A A

6082A B

← crack propagation



fatigue crack

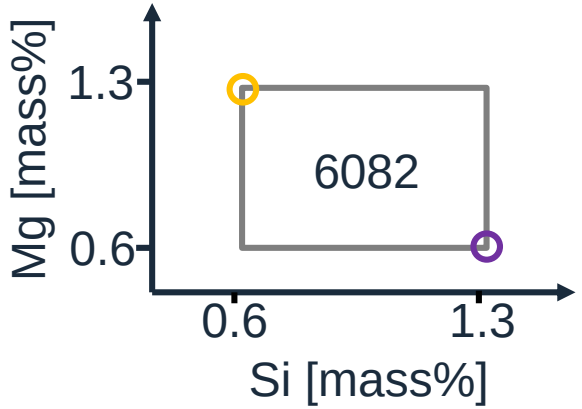
machined notch

Case	Crack extension	K_{IA} versus K_{IAPP}	Judge
I	$(a_{scc}-a_{pre}) \leq 0.16$ mm	$K_{IA} < K_{IAPP}$	invalid
II		$K_{IA} \geq K_{IAPP}$	pass
III	$(a_{scc}-a_{pre}) > 0.16$ mm	$K_{IA} \leq K_{IAPP}$	fail
IV		$K_{IA} > K_{IAPP}$	invalid

- 0.1 $MPam^{1/2}$

a_{scc}: Crack length after stress corrosion cracking test
a_{pre}: Crack length before stress corrosion cracking test (after precracking)
K_{IA}: Stress intensity factor after stress corrosion cracking test
K_{IAPP}: Stress intensity factor before stress corrosion cracking test

In case of variant B crack propagation due to stress corrosion cracking (blue to yellow): 1.3 mm



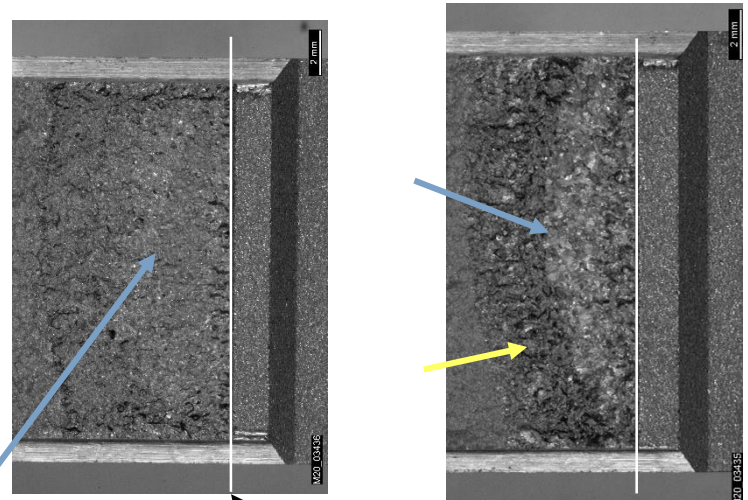
Due to hardware issues the last 4 weeks of stress corrosion cracking were performed at 20°C and 100 %rh

2. 30°C + 85 %rh

6082A A

6082A B

← crack propagation



fatigue precrack

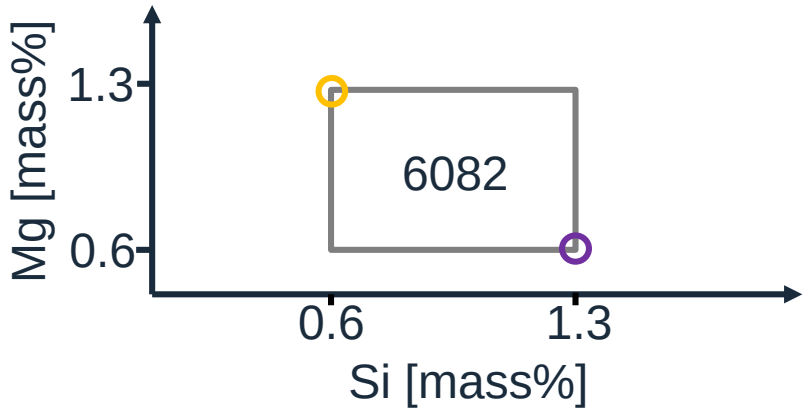
machined notch

In case of variant B crack propagation due to stress corrosion cracking (blue to yellow): 1.3mm

Case	Crack extension	K_{IA} versus K_{IAPP}	Judge
I	$(a_{scc}-a_{pre}) \leq 0.16$ mm	$K_{IA} < K_{IAPP}$	invalid
II		$K_{IA} \geq K_{IAPP}$	pass
III	$(a_{scc}-a_{pre}) > 0.16$ mm	$K_{IA} \leq K_{IAPP}$	fail
IV		$K_{IA} > K_{IAPP}$	invalid

- 0.1 $MPam^{1/2}$

a_{scc}: Crack length after stress corrosion cracking test
a_{pre}: Crack length before stress corrosion cracking test (after precracking)
K_{IA}: Stress intensity factor after stress corrosion cracking test
K_{IAPP}: Stress intensity factor before stress corrosion cracking test

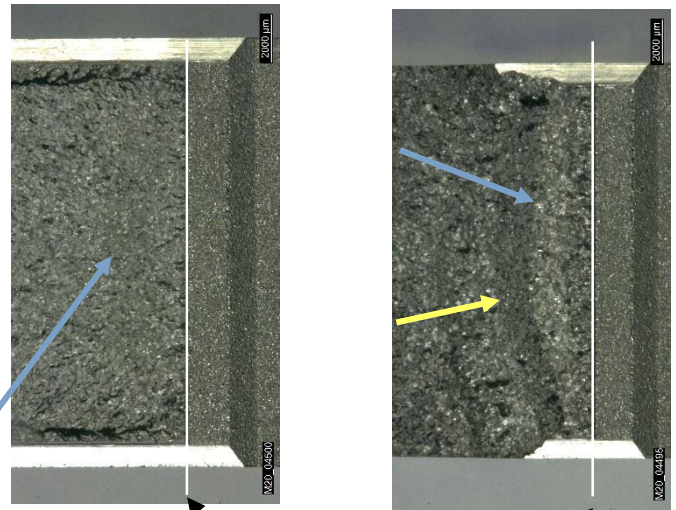


3. 30°C + 98 %rh

6082A A

6082A B

← crack propagation



fatigue precrack

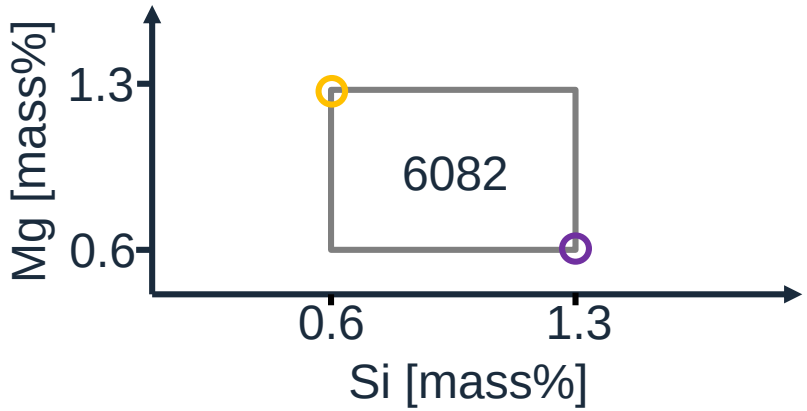
machined notch

In case of variant B crack propagation due to stress corrosion cracking (blue to yellow): 1.6 mm

Case	Crack extension	K_{IA} versus K_{IAPP}	Judge
I	$(a_{scc}-a_{pre}) \leq 0.16$ mm	$K_{IA} < K_{IAPP}$	invalid
II		$K_{IA} \geq K_{IAPP}$	pass
III	$(a_{scc}-a_{pre}) > 0.16$ mm	$K_{IA} \leq K_{IAPP}$	fail
IV		$K_{IA} > K_{IAPP}$	invalid

- 0.5 $MPam^{1/2}$

a_{scc}: Crack length after stress corrosion cracking test
a_{pre}: Crack length before stress corrosion cracking test (after precracking)
K_{IA}: Stress intensity factor after stress corrosion cracking test
K_{IAPP}: Stress intensity factor before stress corrosion cracking test

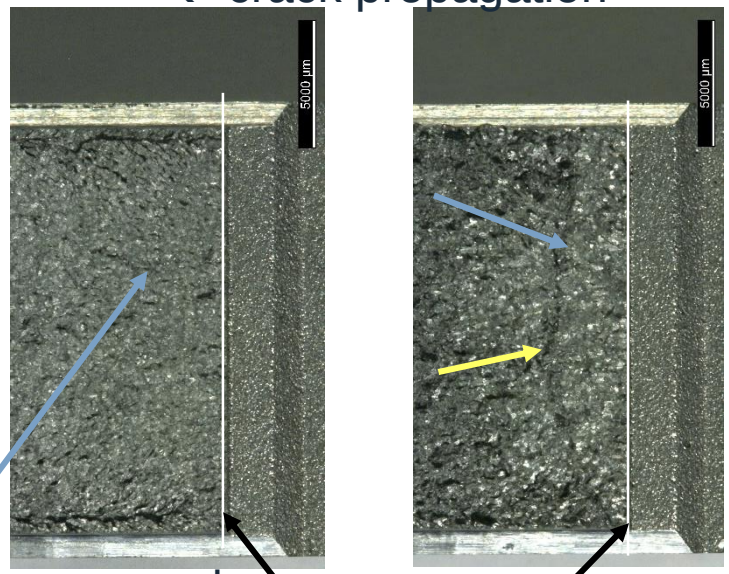


4. 20°C + 85 %rh

6082A A

6082A B

← crack propagation



fatigue precrack

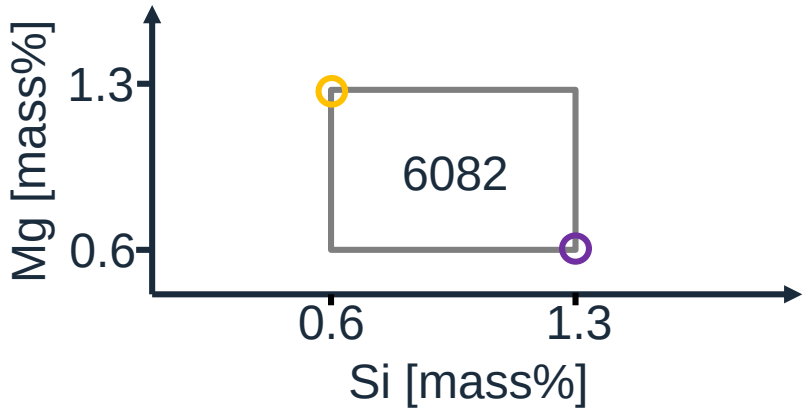
machined notch

In case of variant B crack propagation due to stress corrosion cracking (blue to yellow): 0.34 mm

Case	Crack extension	K_{IA} versus K_{IAPP}	Judge
I	$(a_{scc}-a_{pre}) \leq 0.16$ mm	$K_{IA} < K_{IAPP}$	invalid
II		$K_{IA} \geq K_{IAPP}$	pass
III	$(a_{scc}-a_{pre}) > 0.16$ mm	$K_{IA} \leq K_{IAPP}$	fail
IV		$K_{IA} > K_{IAPP}$	invalid

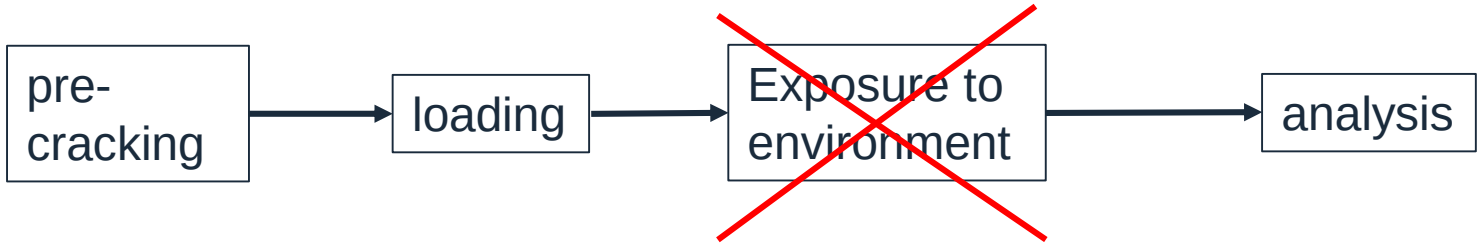
- 0.9 $MPam^{1/2}$

a_{scc}: Crack length after stress corrosion cracking test
a_{pre}: Crack length before stress corrosion cracking test (after precracking)
K_{IA}: Stress intensity factor after stress corrosion cracking test
K_{IAPP}: Stress intensity factor before stress corrosion cracking test



9th specimen

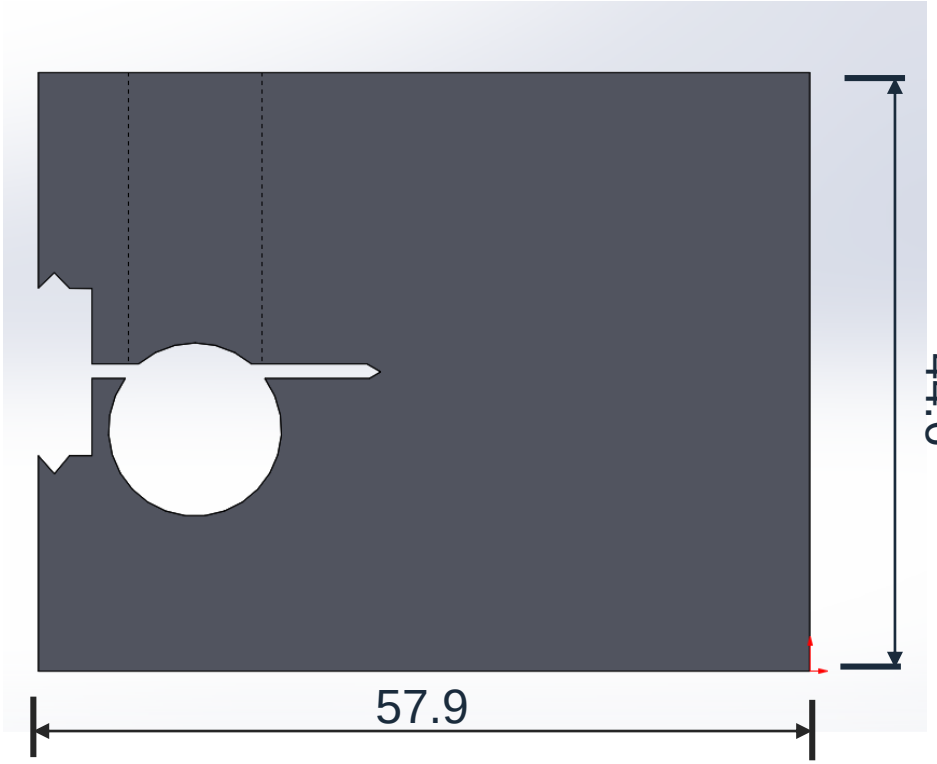
To verify that 6082 B cracked under the influence of the environment and not only by loading, we have the following proposal:



Reason: The loading was close to the critical stress intensity factor.

→ No crack propagation was investigated.
→ The crack propagation from the SCC testing is truely based on the humid air environment.

Specimen Geometry: Wedge Opening Load (WOL)



wire-electro discharge machining

specimen thickness 18 mm

DIN EN ISO 7539-6:2018-12

Heat treatment

EN AW-6082A Variant A and B

At beginning: cast condition F
Target: Condition T6/T62

raw material: Plate 20 mm

- solution heat treatment at 540°C, 130 min
- quenching in water <40°C
- aging at 170°C, 10h
- cool down in air

(according to DIN 29 850 and Aluminium-Zentrale Merkblatt W7)

Pre-cracking parameters and Compliance

according to ASTM E399 and HPIS E 103

Target K after 1.8 mm of crack propagation: 8 $MPam^{1/2}$

1. 0.8 mm crack propagation: R= 0.1; F_{max}=2500 N
2. In total 1.8 mm crack propagation: R=0.1; F_{max}=2000 N

Compliance (before and after precracking):
3 Cycles
500 N - 1500 N
0.1 mm/min COD-velocity

→ Compliance is performed to determine the crack length. Due to the side grooves optical determination is not possible.