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Overview of Elastic-Plastic Fracture Testing (with Hydrogen)

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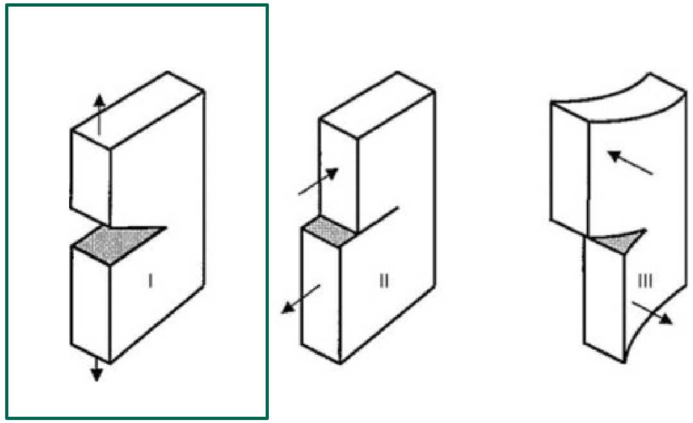
Goals of Presentation

- Provide brief overview of why we use Elastic-Plastic Fracture Testing
- Describe what types of Coupons we commonly test
- Show overview of fracture test methodology
- Show examples of similitude in J_{IH} values calculated from different geometries
- Summarize fracture resistance values measured in H_2

Fracture Toughness vs Fracture Resistance

Fracture toughness – a quantitative way of expressing a material's resistance to fracture when a crack is present.

- K_{IC} is plane-strain fracture toughness in mode I loading which is a *material property* (like yield strength), meaning it is independent of size of the sample
  - Achieved when size requirements are met



Fracture Resistance (K_{JIH}) in hydrogen – is terminology that we often use to described a material's resistance to fracture in H_2

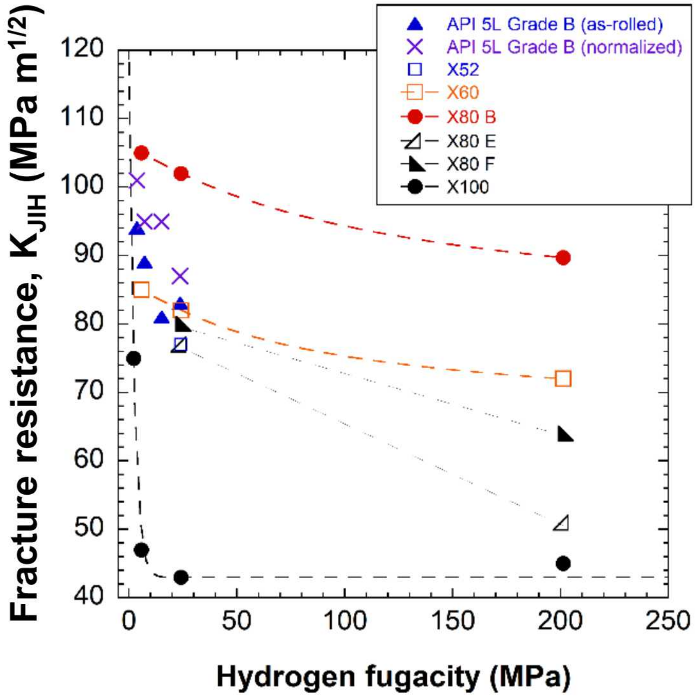
- Can depend on environment

For X100 pipeline steel

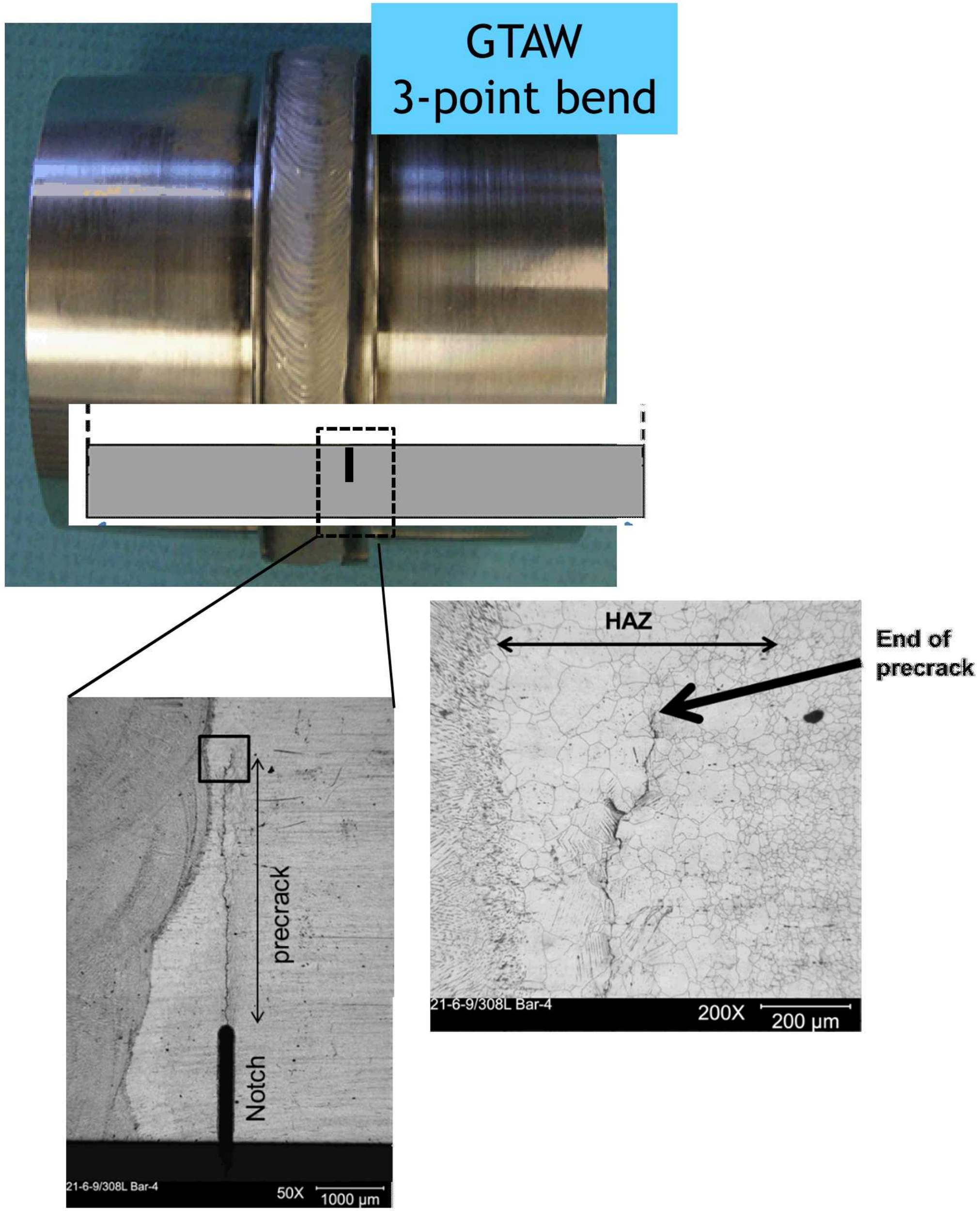
In Air, K_{JIC} > 200 MPa $m^{1/2}$

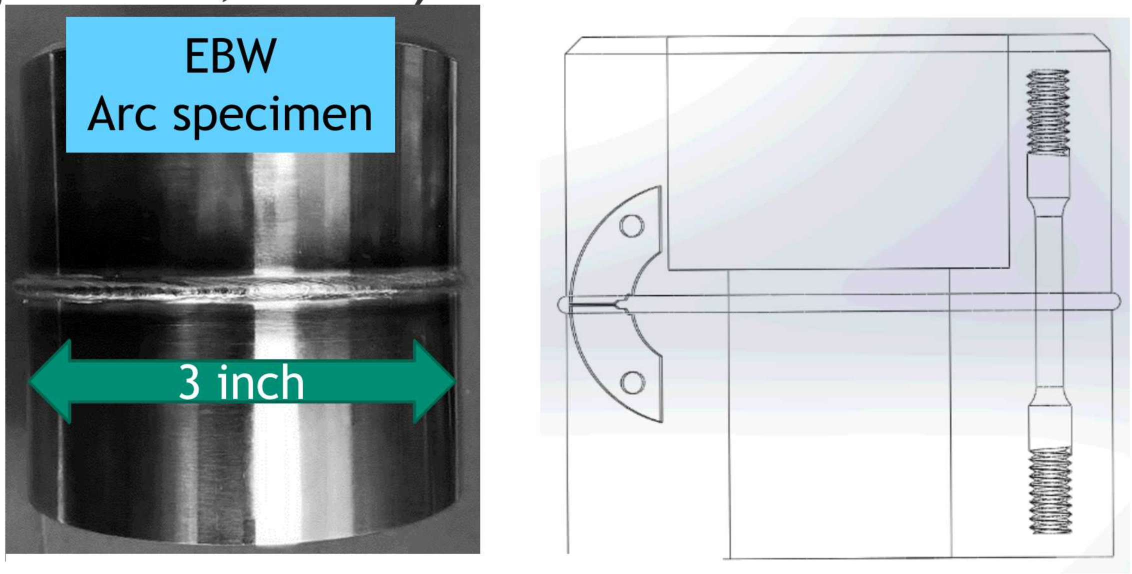
In 2.1 MPa H_2, K_{JIH} = 75 MPa $m^{1/2}$

In 21 MPa H_2, K_{JIH} = 43 MPa $m^{1/2}$

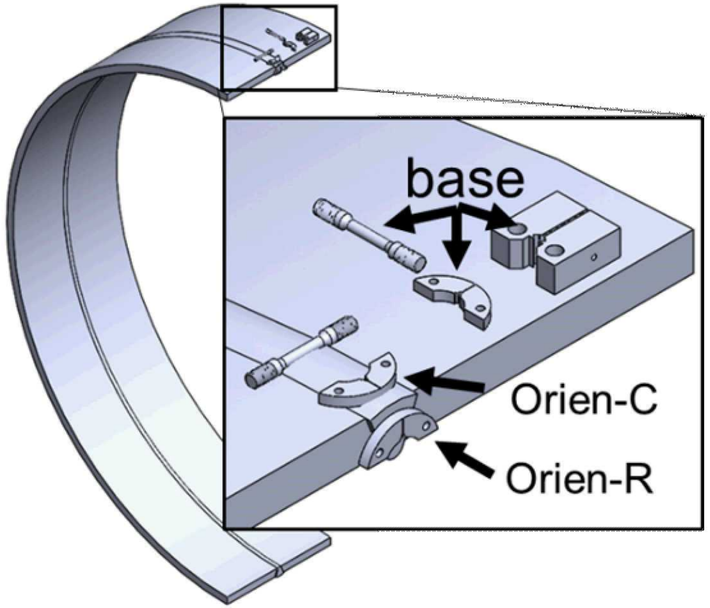


Material constraints necessitate a variety of coupon geometries to characterize fracture behavior (e.g. welds, HAZ)





X100 weld



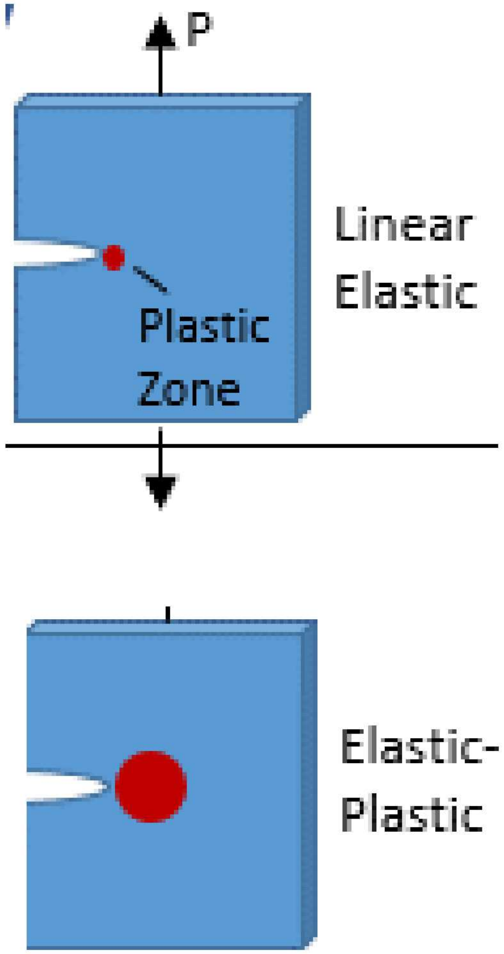
Linear Elastic Fracture Mechanics (LEFM) or Elastic-Plastic Fracture Mechanics (EPFM)

Assumptions for LEFM:

- Valid only when the size of plastic zone is small compared to size of crack (small-scale yielding)
- To ensure small-scale yielding, very strict dimensional requirements are necessary

Typically need to have a fairly brittle material (low K_{IC}) or a very large specimen in order to satisfy LEFM

- Ceramics $K_{IC} \sim 1$ MPa $m^{1/2}$ (LEFM)
- Aluminum $K_{IC} \sim 20\text{-}30$ MPa $m^{1/2}$ (LEFM or EPFM)
- Ferritic Steels $K_{IC} > 50$ MPa $m^{1/2}$ (LEFM or EPFM)
- Austenitic Stainless Steel $K_{IC} > 200 - 600$ MPa $m^{1/2}$ (EPFM)



https://mechanicalc.com/reference/fracture-mechanics

We typically *do not use* LEFM when analyzing test data from materials used for hydrogen gas containment

Validity criteria for ASTM E399 (LEFM) – Very straightforward

Plane strain fracture toughness (K_{IC}) is crack-extension resistance under conditions of crack-tip plane strain in Mode I for slow rates of loading under predominantly linear-elastic conditions and negligible plastic-zone adjustment.

Designation: E399 – 12$^{\varepsilon 3}$

Standard Test Method for Linear-Elastic Plane-Strain Fracture Toughness K_{Ic} of Metallic Materials[1]

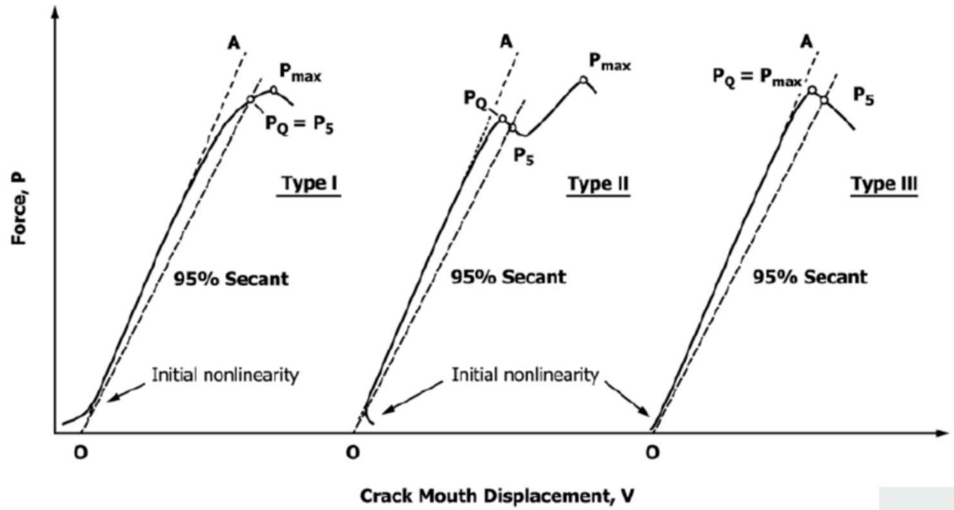
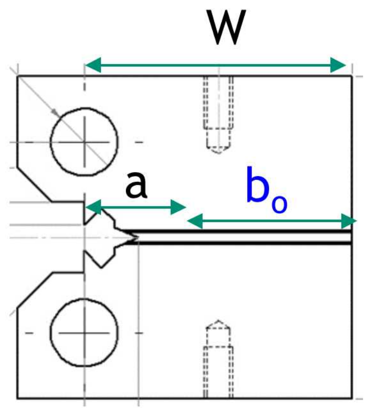


FIG. 7 Principal Types of Force-Displacement (CMOD) Records

For Compact Tension: $K_Q = \frac{P_Q}{\sqrt{BB_N}\sqrt{W}} \cdot f\left(\frac{a}{W}\right)$



b_o = W-a
(remaining ligament)

Typically,
W/B = 2, a/W =0.5
B = thickness

If you pass this criteria:

$b_o > 2.5\,(K_Q/YS)^2$ ensures SSY

$P_{max}/P_Q < 1.1$ ensures overall plasticity is small

Then $K_Q = K_{IC}$

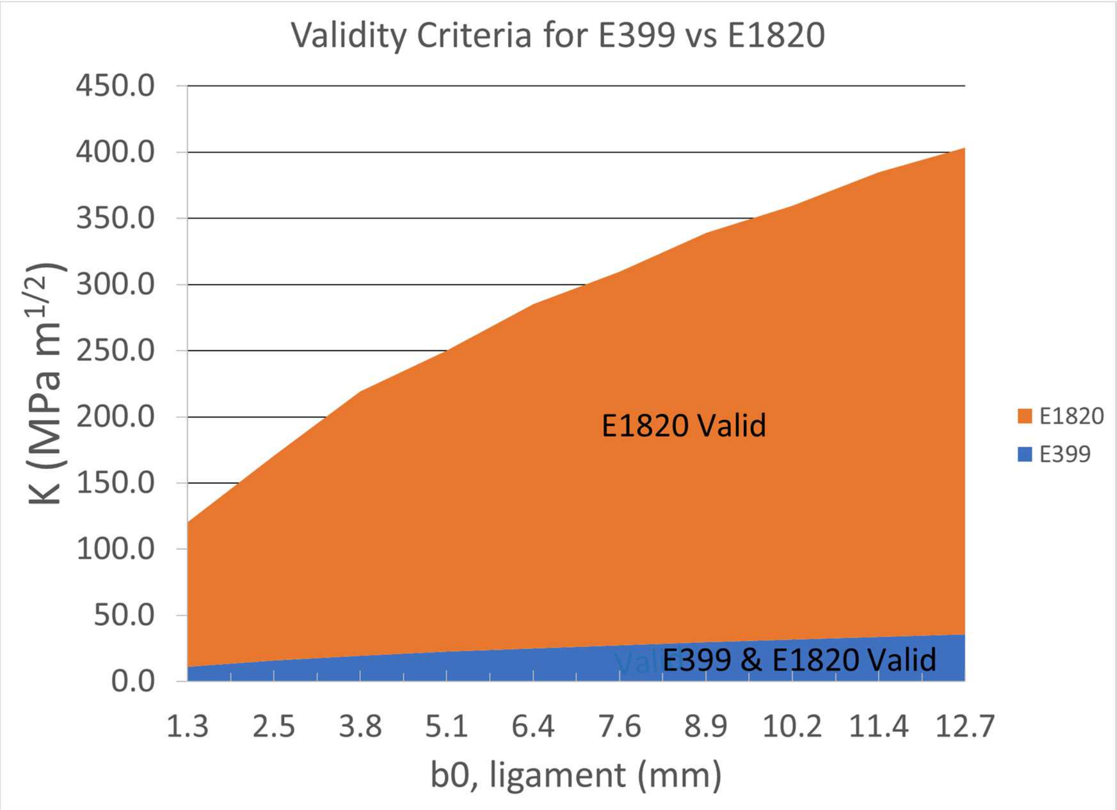
	E399
K_{IC} (MPa $m^{1/2}$)	Ligament (bo) (mm)
20	4.1
50	25.4
200	401.3

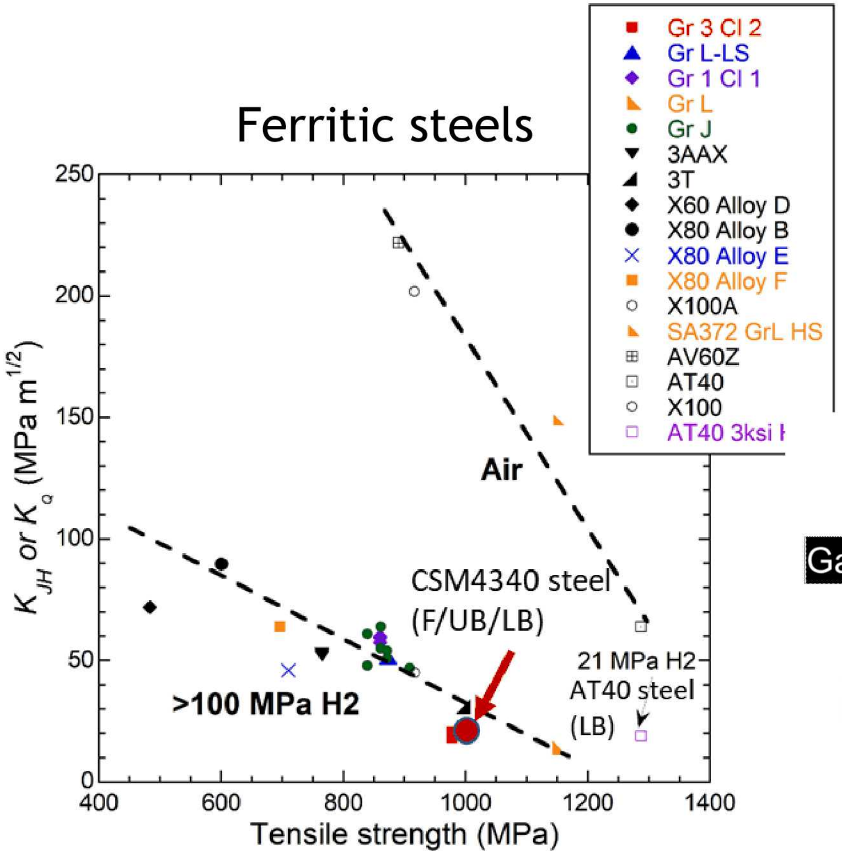
Assume: YS= 500 MPa

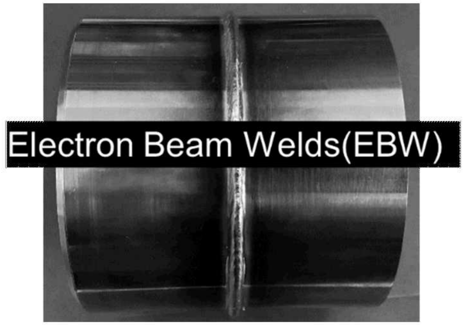
We typically use Elastic-Plastic Fracture Testing

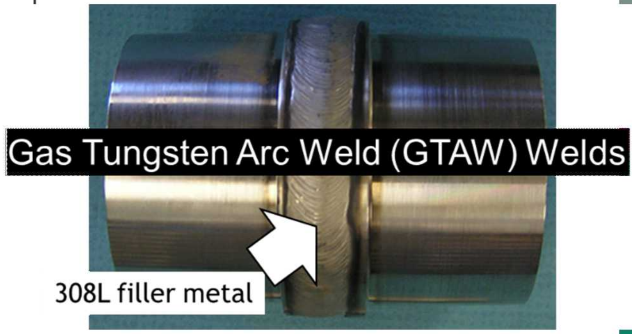
For hydrogen containment – we purposefully choose tough materials that have large amounts of plasticity and therefore violate LEFM assumptions

Hydrogen reduces fracture resistance of most materials which tends to decrease with increasing strength









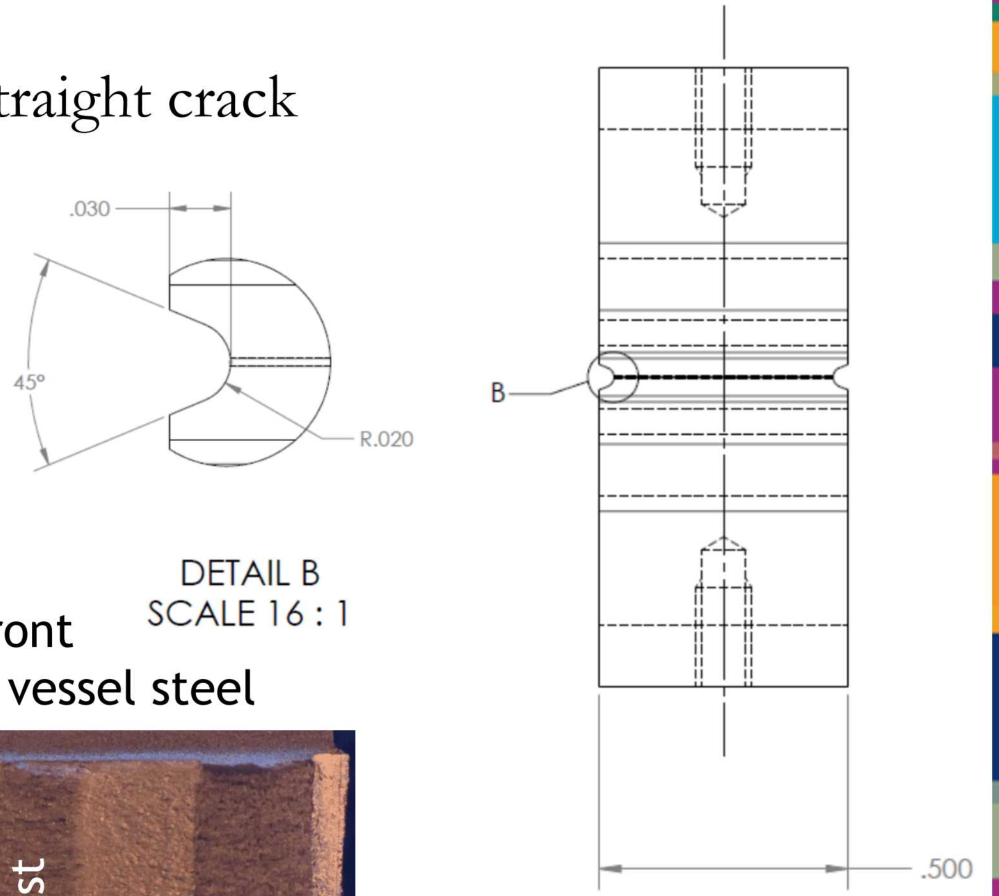
Crack Uniformity & Side Grooves

Side grooves are highly recommended to help ensure a straight crack front.

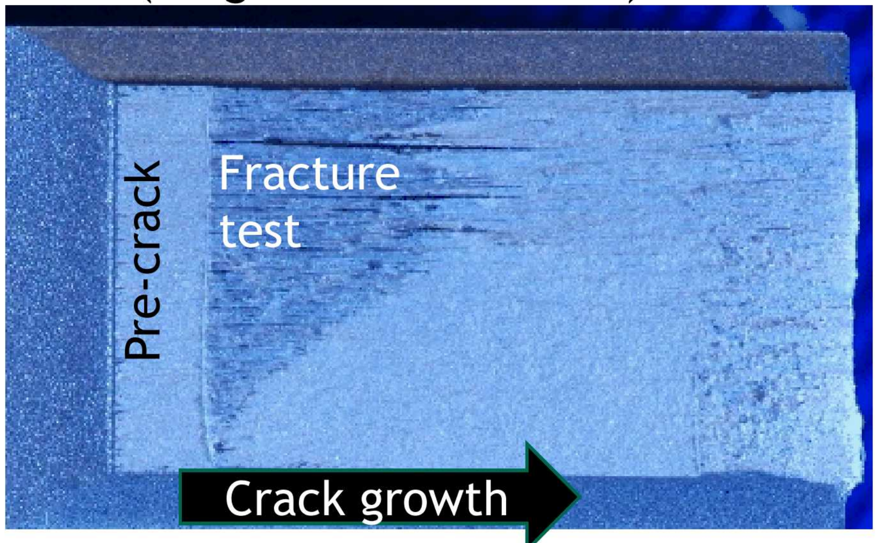
- Reduce thickness up to 25%

Crack uniformity

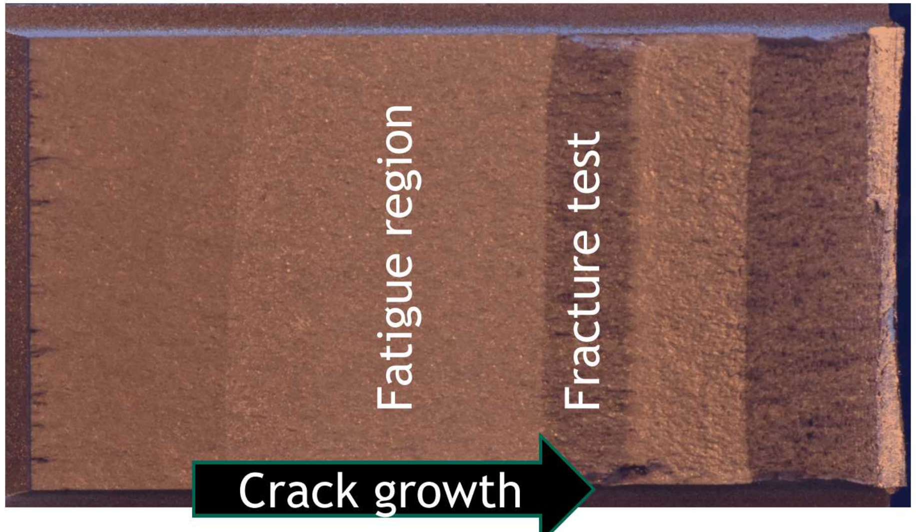
- Crack shall not differ more than $0.1(b_o B_N)^{1/2}$



Non-uniform crack front
(Forged Stainless Steel)



Uniform crack front
SA372J Pressure vessel steel



We follow ASTM E1820 for fracture testing

Size restrictions are much more relaxed because it can accommodate large scale yielding

J-integral is a path-independent contour integral used to characterize near-crack-tip deformation field in linear and non-linear elastic materials.

Relationship between J and K can be used to infer equivalent K_{IC} in high toughness materials in which K_{IC} testing would require unreasonably large specimens

$$K = \sqrt{\frac{EJ}{1-\nu^2}}$$

Multi-specimen or single-specimen approach can be used

→ Can determine crack length by either:

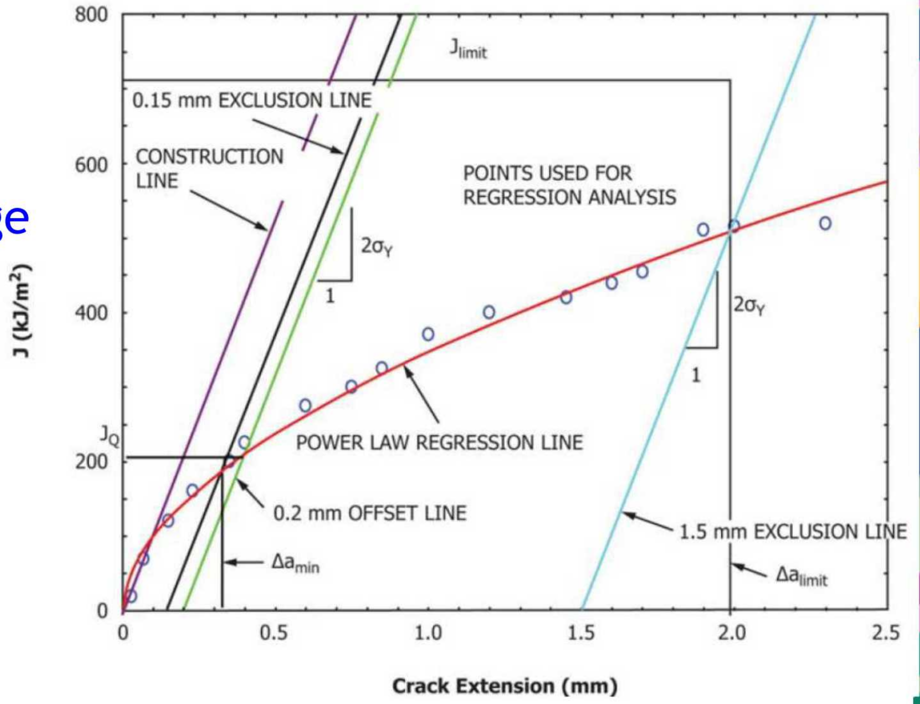
- Incremental unloading to measure compliance
- Continuous rising displacement using Direct Current Potential Difference (DCPD)

J_Q represents fracture energy at select crack extension

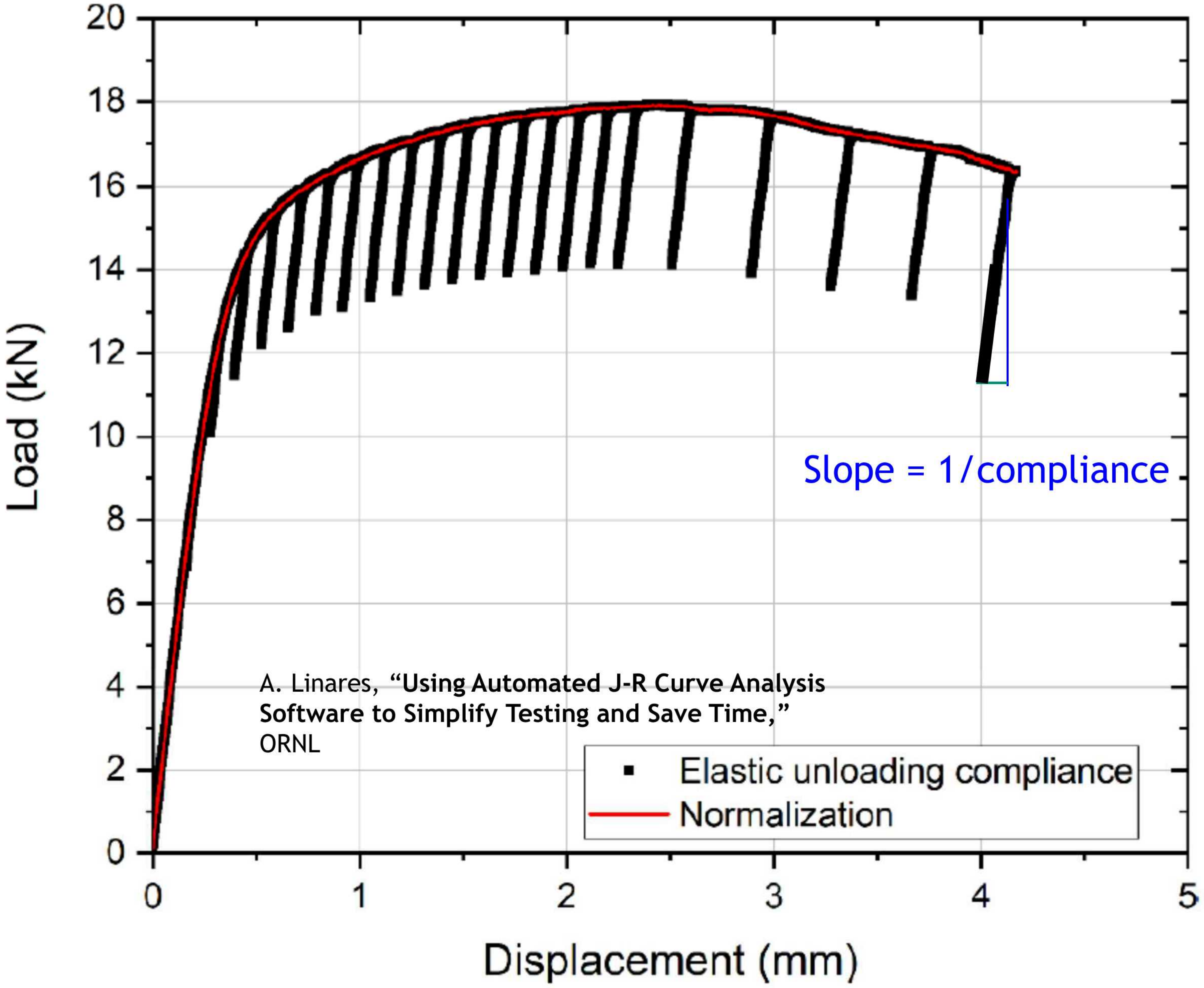
- Intersection of J-R curve with 0.2 mm construction line

Designation: E1820 – 18a$^{\epsilon1}$

Standard Test Method for Measurement of Fracture Toughness[1]



Unloading Compliance Method for E1820



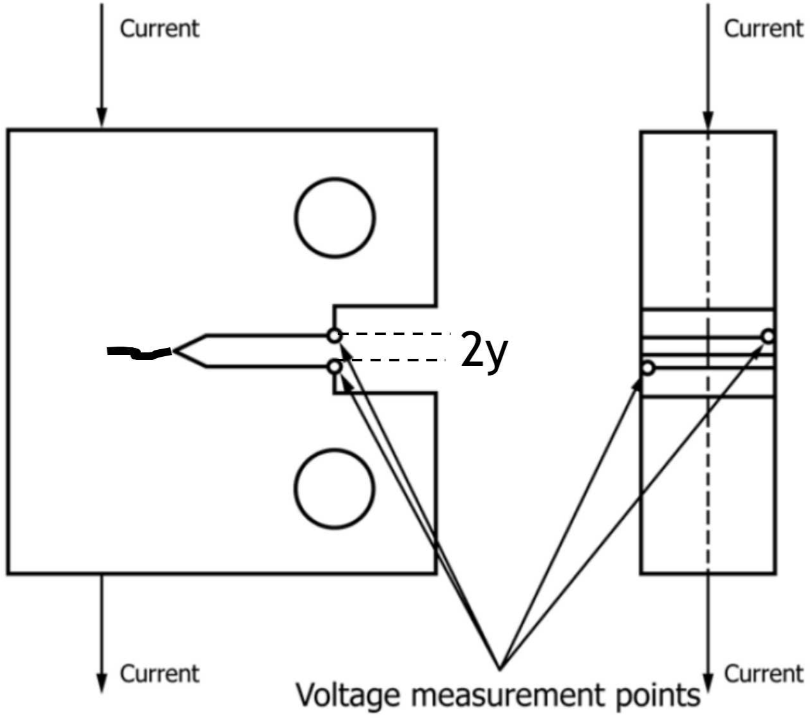
A. Linares, **"Using Automated J-R Curve Analysis Software to Simplify Testing and Save Time,"** ORNL

Compliance can be determined by:

1) measuring the unloading slopes (Compliance = $\Delta v / \Delta P$)
2) using DCPD to determine crack length and calculating C_{LL}(compliance as below)

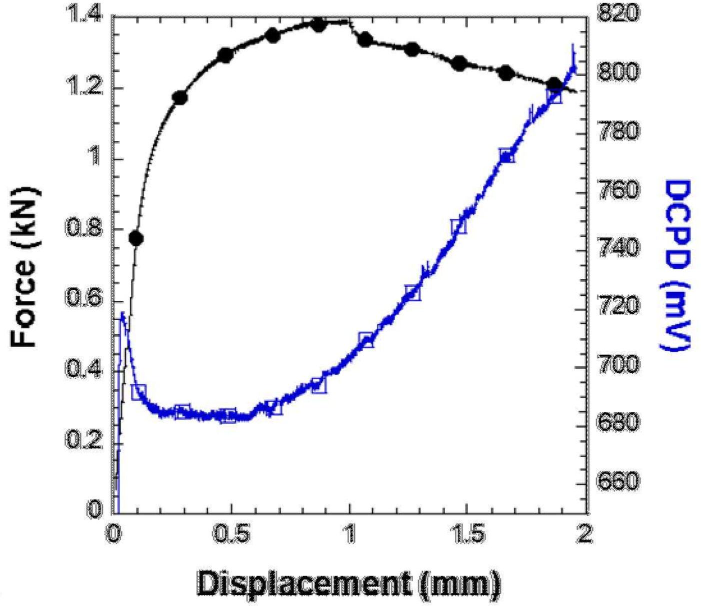
$$C_{LL(i)} = \frac{1}{EB_e}\left(\frac{W+a_i}{W-a_i}\right)^2\left[2.1630+12.219\left(\frac{a_i}{W}\right)-20.065\left(\frac{a_i}{W}\right)^2 - 0.9925\left(\frac{a_i}{W}\right)^3+20.609\left(\frac{a_i}{W}\right)^4-9.9314\left(\frac{a_i}{W}\right)^5\right] \quad \text{(A2.11)}$$

Direct Current Potential Difference (DCPD)



Concept utilizes principals of V = IR
→I = constant
→So as the crack extends, R ↑, V ↑

For CT coupon:



$$\frac{a}{W} = \frac{2}{\pi}\cos^{-1}\left[\frac{\cosh\left(\frac{\pi y}{2W}\right)}{\cosh\left\{\frac{V}{V_0}\cosh^{-1}\left[\frac{\cosh\left(\frac{\pi y}{2W}\right)}{\cos\left(\frac{\pi a_{0,bl}}{2W}\right)}\right]\right\}}\right]$$

Monitor crack length through closed-form analytical expressions relating DCPD to crack length (geometry specific)

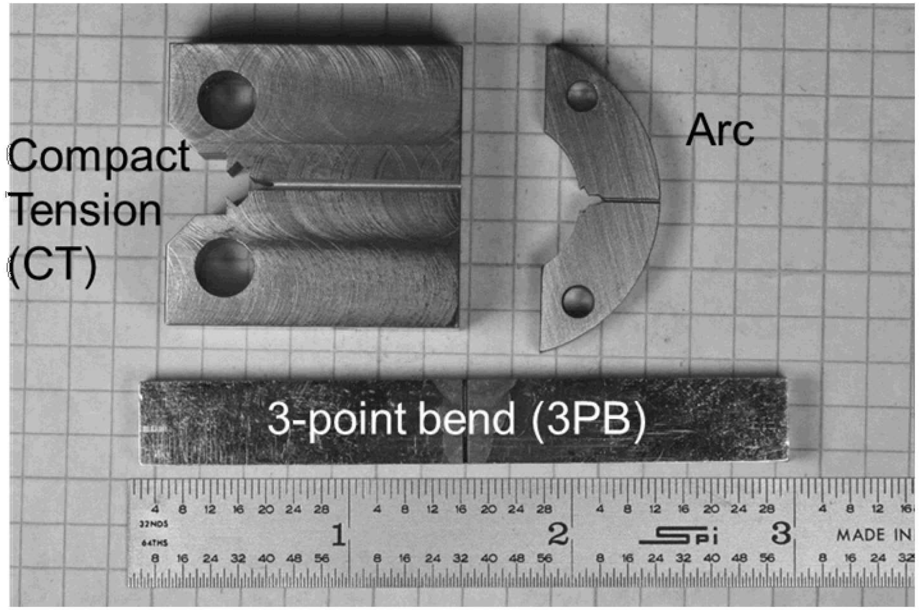
Challenges affecting DCPD: thermal drift, specimen heating, stray electric fields, non-uniform crack fronts, plasticity
Mitigation Strategies: Current switching, reference specimen, interrupted tests, wire selection & positioning

How we calculate J according to ASTM E1820

1) Precrack to ensure we have sharp crack tip
2) Place DCPD probes on specimen to monitor crack length
3) Perform rising displacement fracture test

   Record:

   - Load
   - Crack mouth opening displacement
   - DCPD voltage → to track crack length



*Arc is not actually found in E1820 but we have shown similitude in results with CT and 3PB

$$J = J_{el} + J_{pl} = \underbrace{\frac{K^2(1-\nu^2)}{E}}_{J_{el}} + \underbrace{\frac{\eta A_{pl}}{B_N b_o}}_{J_{pl}}$$

J_{el}: Elastic component

J_{pl}: Plastic component

J_{total} is split into J_{el} and J_{pl}

$$K_{(i)} = \frac{P_{(i)}}{(BB_N W)^{1/2}} f\left(\frac{a_i}{W}\right)$$

P = load

B = thickness

B_N = net thickness

W = width

a = crack length

How we calculate J according to ASTM E1820 (for CT)

$$J = J_{el} + J_{pl} = \frac{K^2(1-\nu^2)}{E} + \frac{\eta A_{pl}}{B_N b_o}$$

where:

A_{pl} = area shown in Fig. A1.2,
B_N = net specimen thickness ($B_N = B$ if no side grooves are present),
b_o = uncracked ligament, $(W - a_o)$, and
η_{pl} = $2 + 0.522 b_o/W$. (geometry factor)

$$A_{pl(i)} = A_{pl(i-1)} + \frac{[P_{(i)} + P_{(i-1)}][v_{pl(i)} - v_{pl(i-1)}]}{2} \quad \text{(A2.10)}$$

where:

$v_{pl(i)}$ = plastic part of the load-line displacement, $v_i - P_{(i)}C_{LL(i)}$, and
$C_{LL(i)}$ = experimental compliance, $(\Delta v/\Delta P)_i$, corresponding to the current crack size, a_i.

→ Compliance can be measured by unloading or inferred from DCPD

$$J_{pl(i)} = \left[J_{pl(i-1)} + \left(\frac{\eta_{pl(i-1)}}{b_{(i-1)}}\right)\frac{A_{pl(i)} - A_{pl(i-1)}}{B_N}\right]\left[1 - \gamma_{(i-1)}\left(\frac{a_{(i)} - a_{(i-1)}}{b_{(i-1)}}\right)\right] \quad \text{(A2.9)}$$

where:

$\eta_{pl(i-1)} = 2.0 + 0.522\, b_{(i-1)}/W$, and
$\gamma_{(i-1)} = 1.0 + 0.76\, b_{(i-1)}/W$.

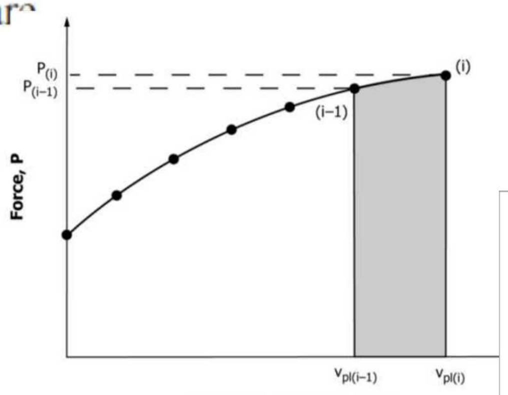
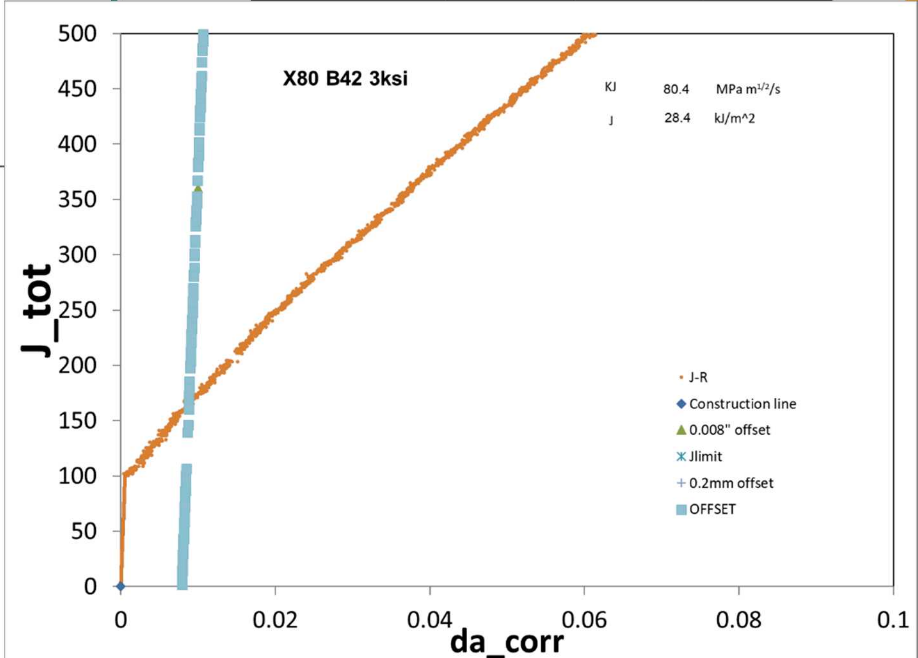


FIG. A1.3 Definition of Plastic Area for Resistance Curve J Calculation

crack length, a	$J_{elastic}$	$J_{plastic}$	J_{total}
0.1	1	2.5	3.5
0.2	1.5	3.5	5



Build J vs Δa curve through numerical integration

Conversion from J to K in ASTM E1820

Designation: E1820 – 18a$^{\epsilon 1}$

Standard Test Method for Measurement of Fracture Toughness[1]

Plane-strain fracture toughness is the value of the stress intensity designated K_{JIc} calculated from J_{Ic} using the equation (and satisfying all of the qualification requirements) specified in this test method.

If these are met:

$B > 10J_Q/S_Y$ and $b_o > 10J_Q/S_Y$

Where:

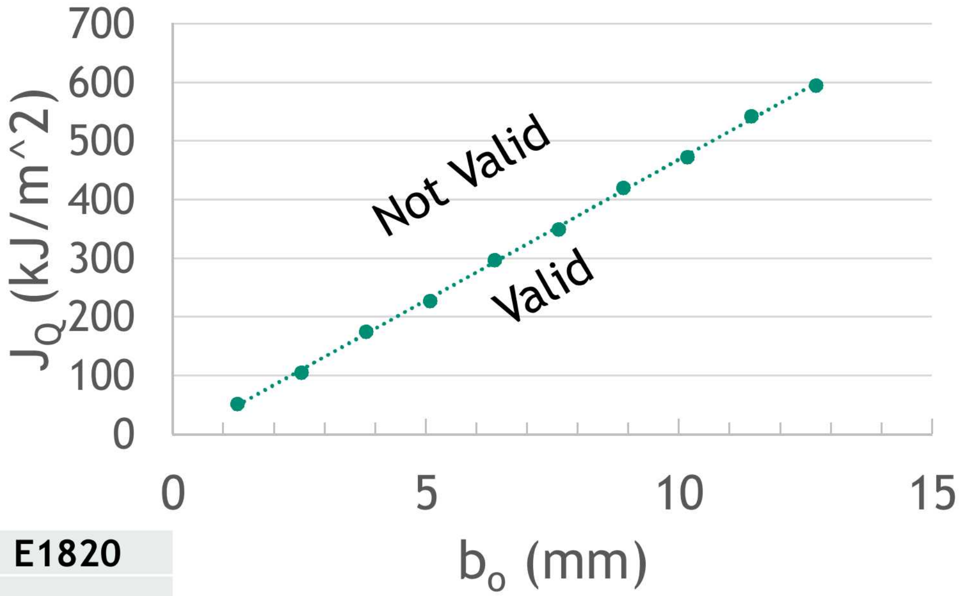
B = thickness

J_Q = intersection at 0.2 mm construction line

S_Y = flow stress (avg of YS and UTS)

b_o = remaining ligament (W-a)

Ligament (b_o) Validity



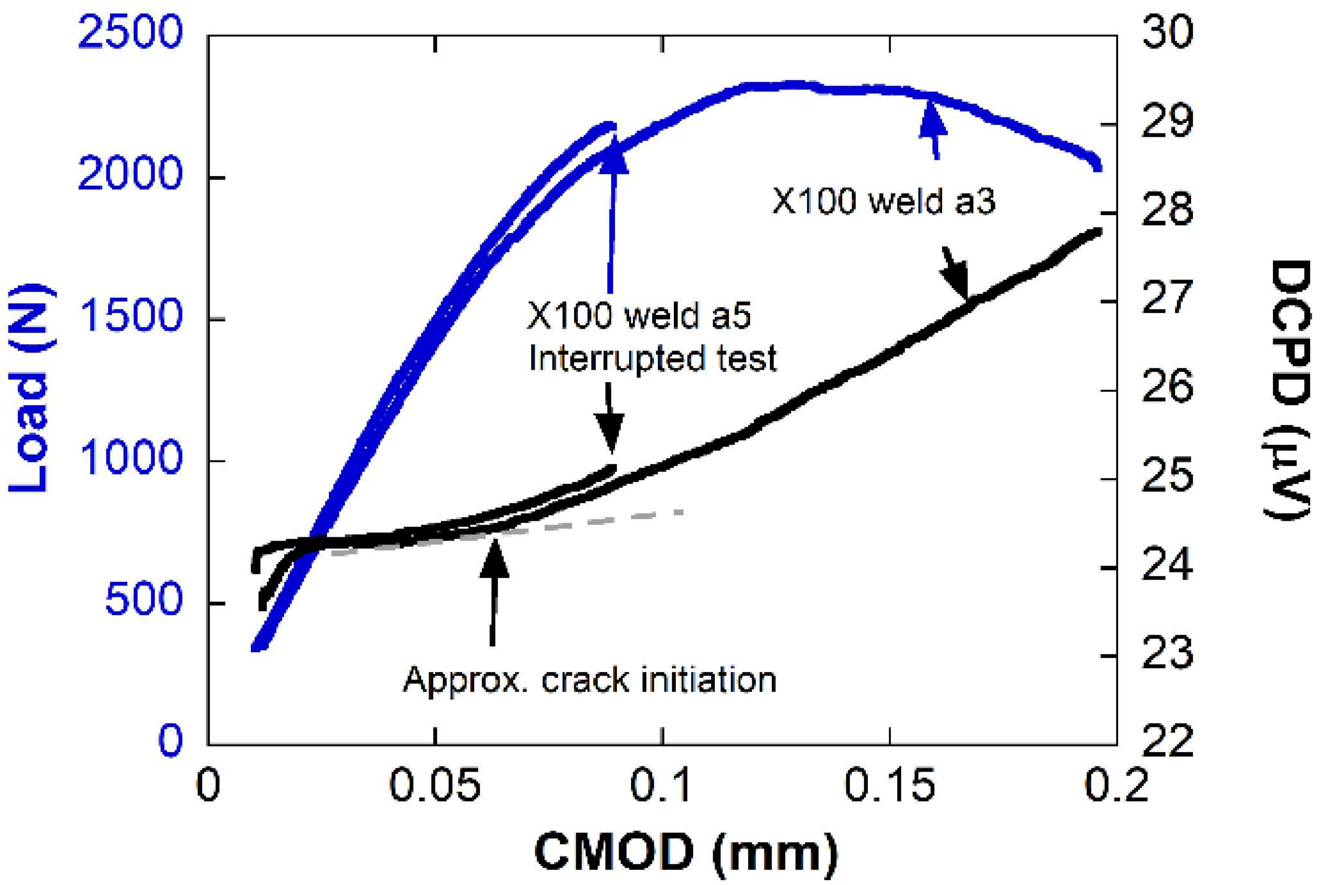
Then can convert to size-independent K_{JIC}:

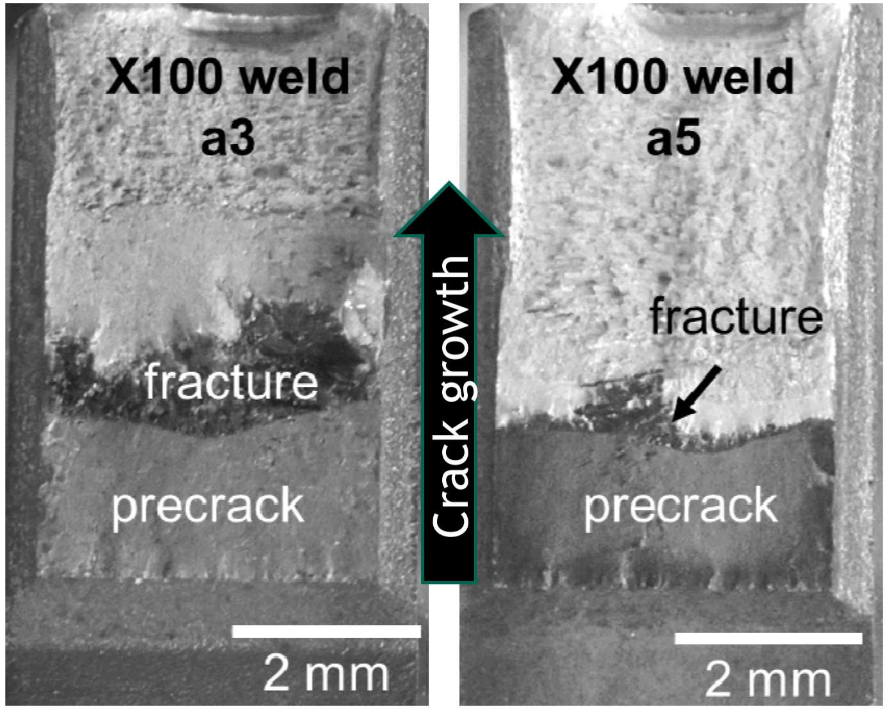
$$K_{JIC} = \sqrt{\frac{EJ_{IC}}{1-v^2}}$$

	E399	E1820
K_{IC} or K_{JIC} (MPa $m^{1/2}$)	Ligament (bo) (mm)	Ligament (bo) (mm)
20	4.1	0.05
50	25.4	0.25
200	401.3	4.32

Assumptions: YS= 500 MPa
Flow stress = 500 MPa

Determination of Crack Initiation Using DCPD





Heat tint at 300C for 1 hr to mark crack extension

Crack lengths measured by DCPD are linearly correct based on physical measurements post test.

$$a_{i,adj} = \frac{a_p - a_{0,bl}}{a_{p,\ predicted} - a_{0,bl}}(a_i - a_{0,bl}) + a_{0,bl},$$

Can improve accuracy of determining crack initiation by interrupted tests

Different Geometries give comparable J_Q values

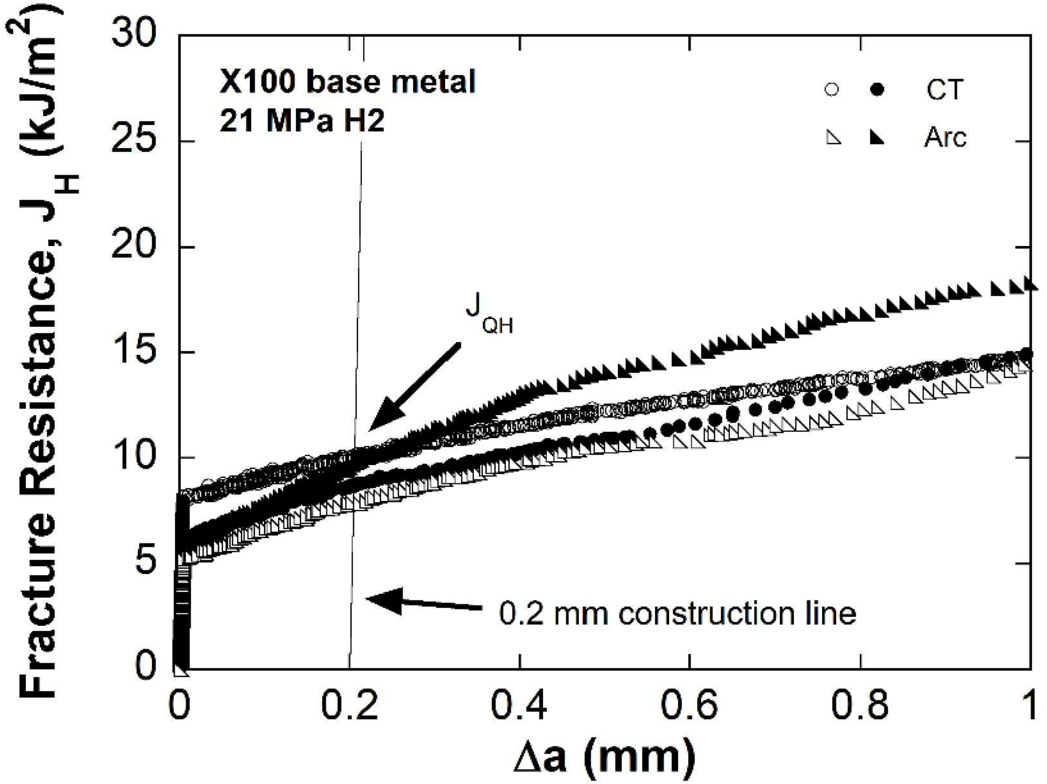
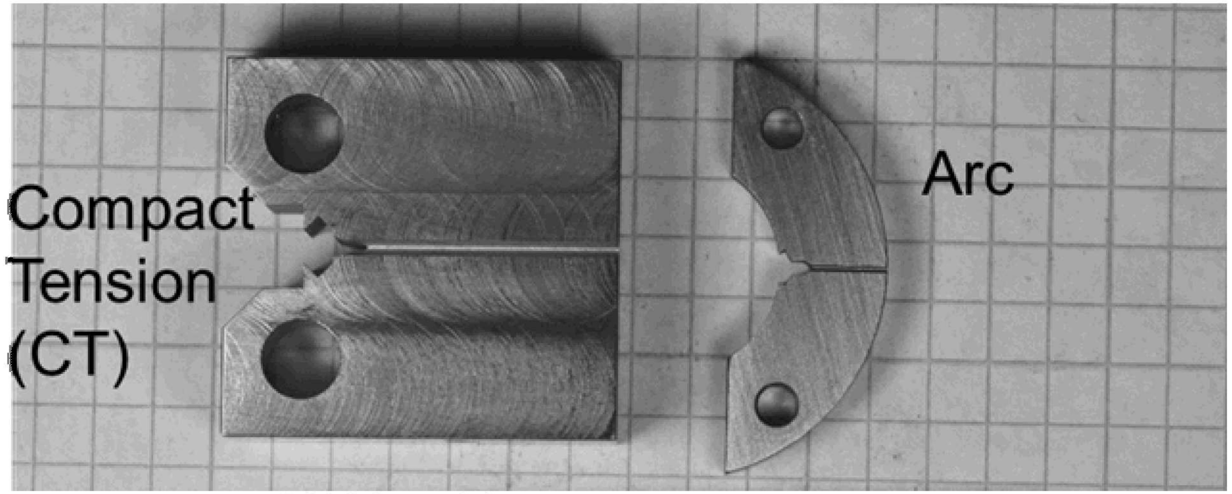
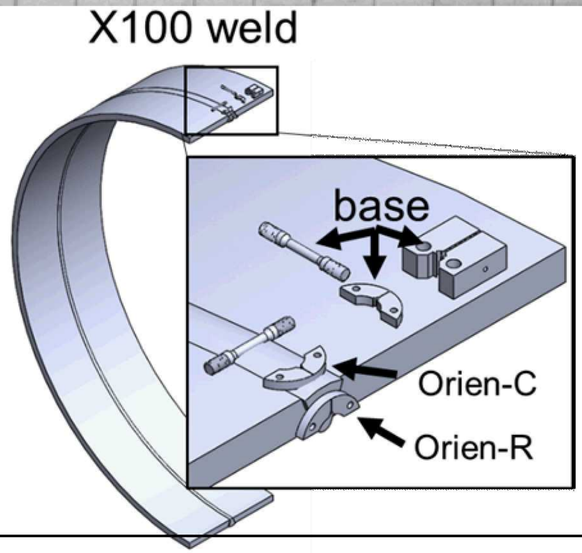


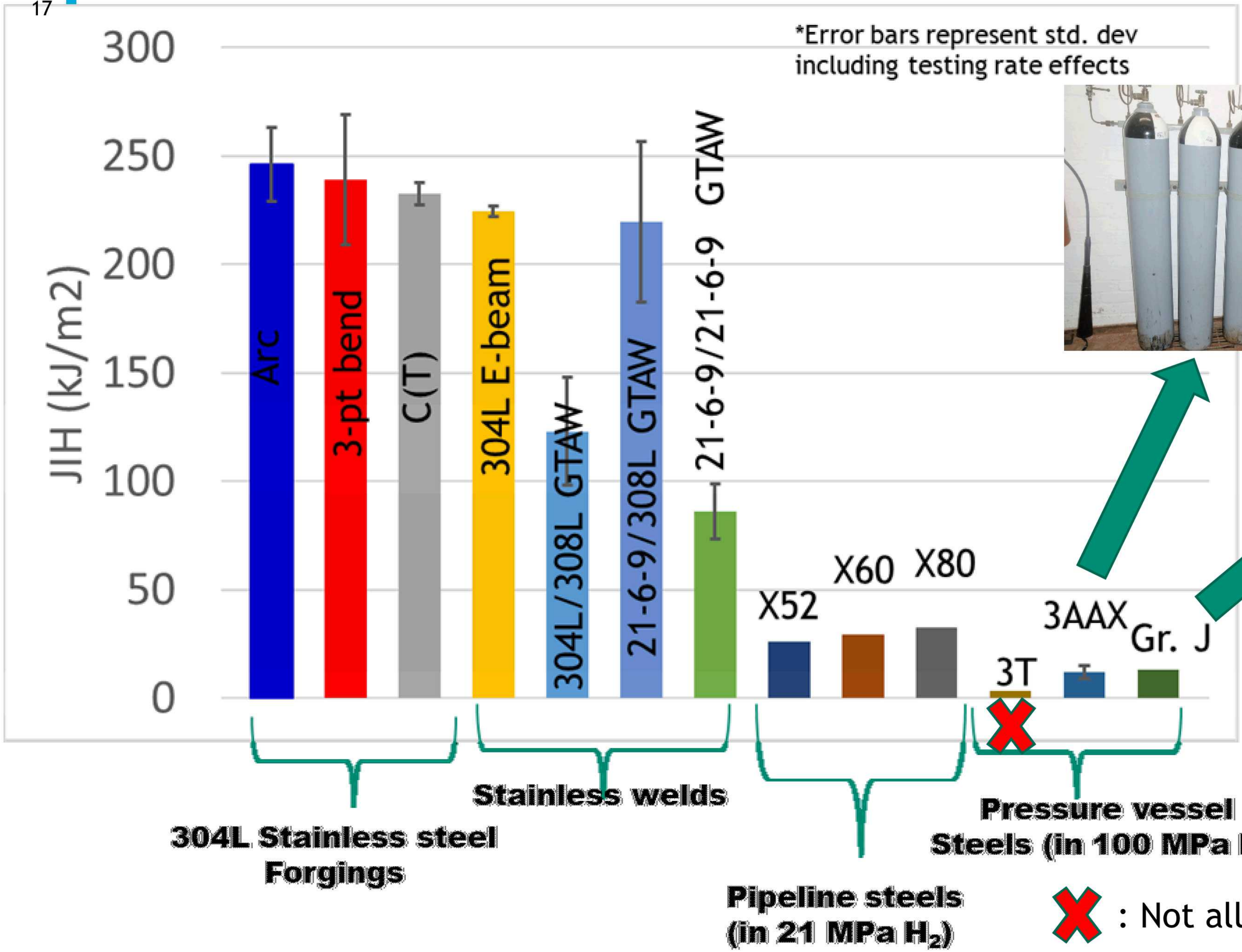
Figure 6 - Comparison of X100 base metal fracture resistance in 21 MPa hydrogen gas for the arc and CT coupons plotted as resistance curves, e.g. J_H vs Δa.

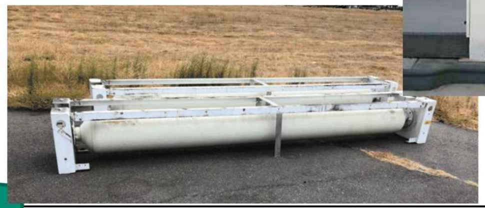




This is significant as it is often difficult to extract CT coupons from welds/HAZ

Stainless steel performance in H_2 relative to other alloy systems

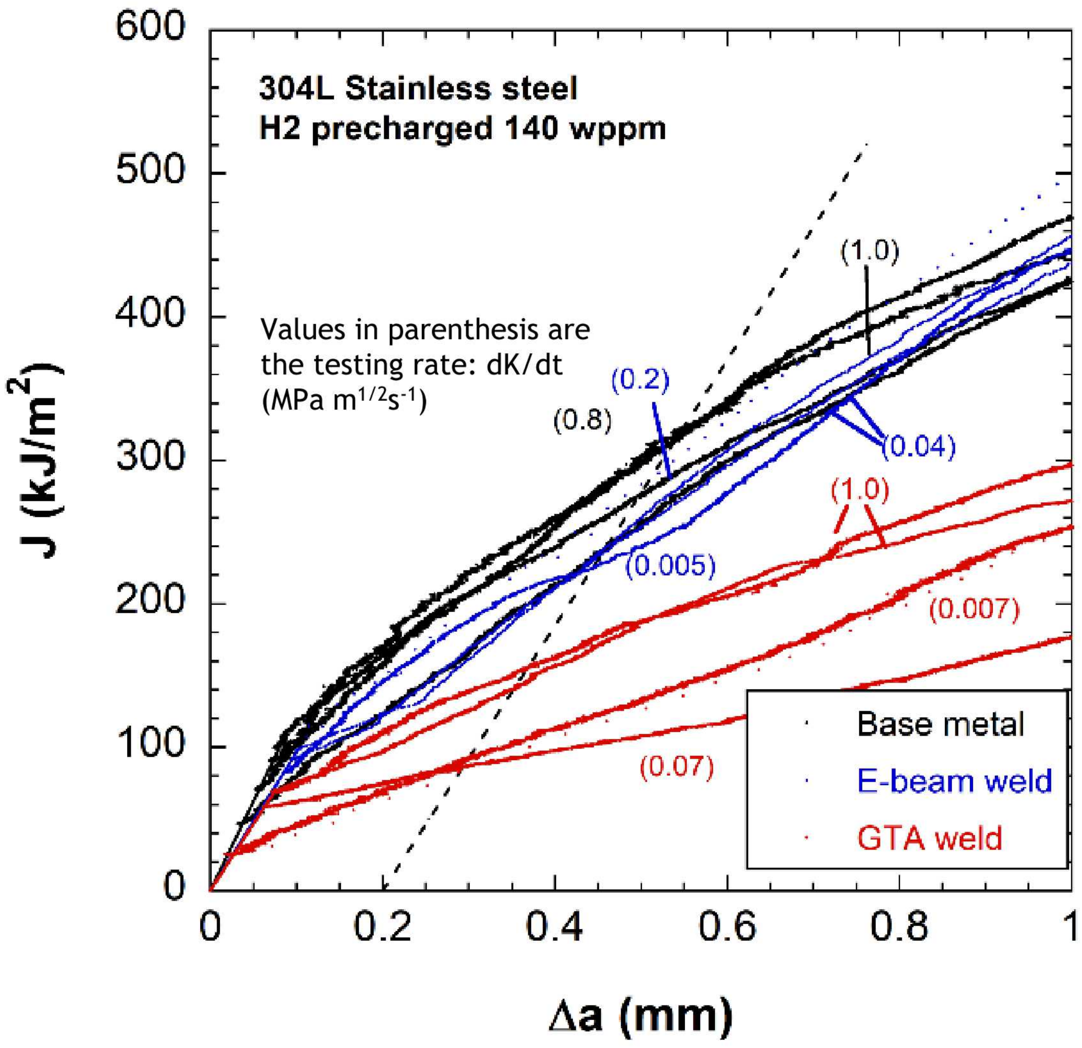


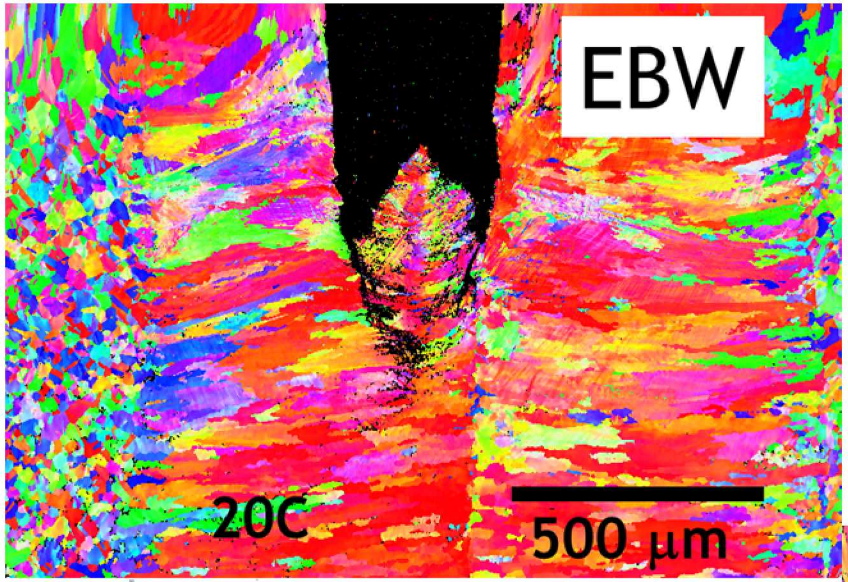


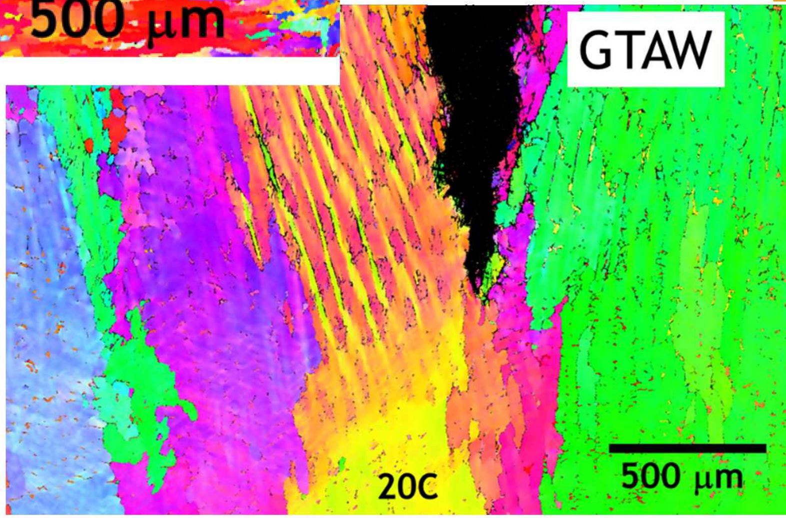
Ref:
San Marchi et al. (2010)
San Marchi et al. (2011)
Jackson et al (2013)
Somerday et al.(2009)

Most of these materials are used in hydrogen infrastructure. Proper design and operation ensures their integrity

Comparison of fracture resistance of austenitic stainless steel welds



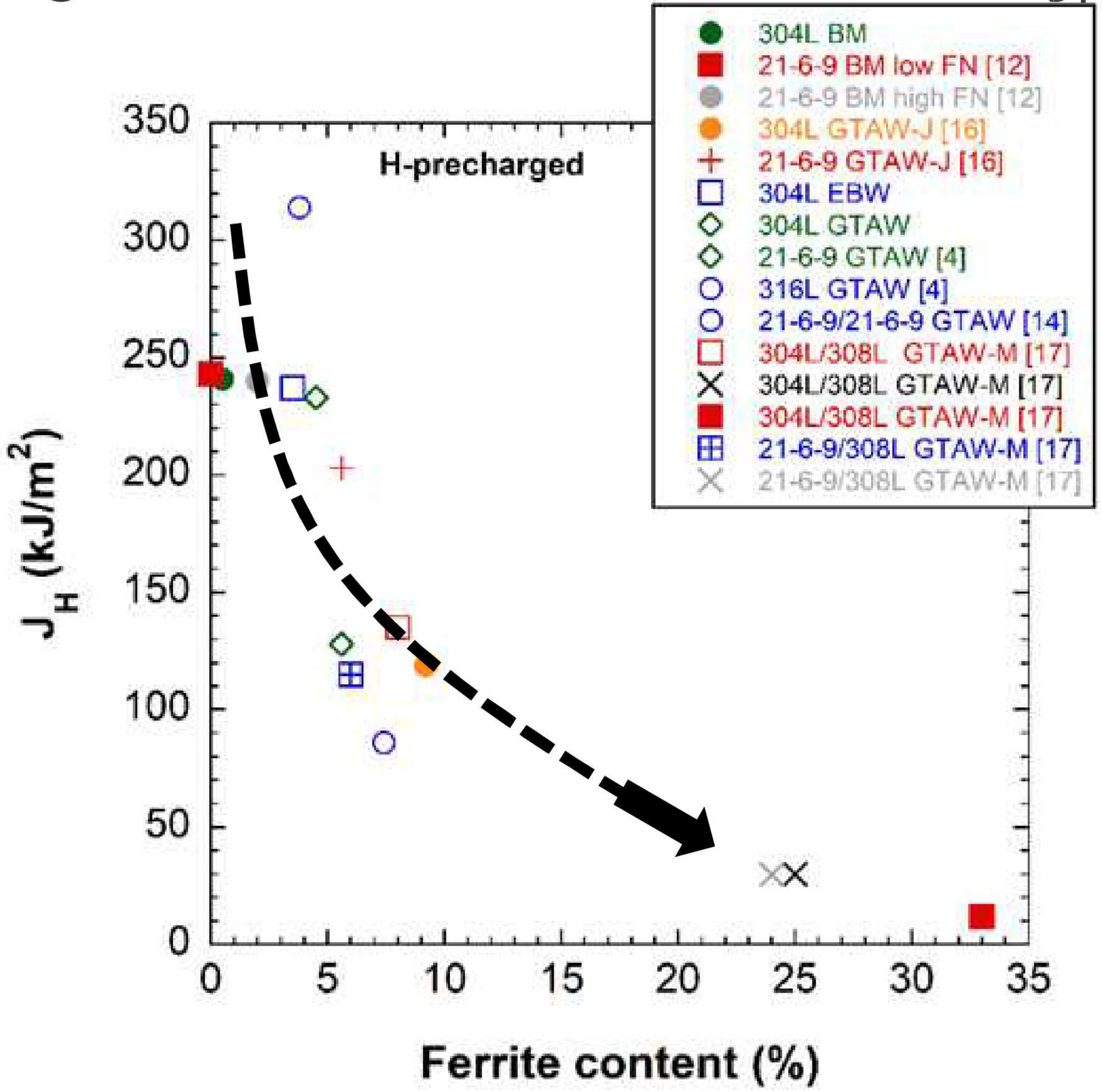




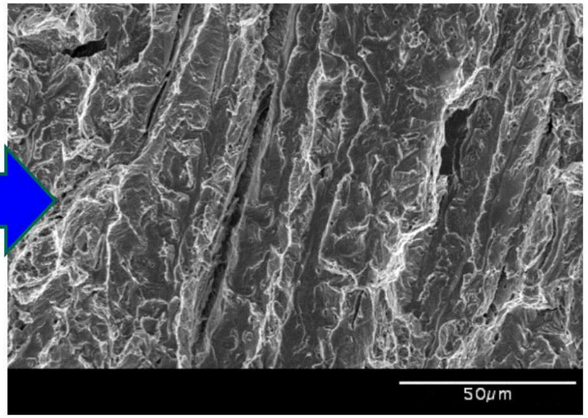
Cracks growth along elongated features

Electron beam welds give comparable fracture resistance (J_H) to forgings

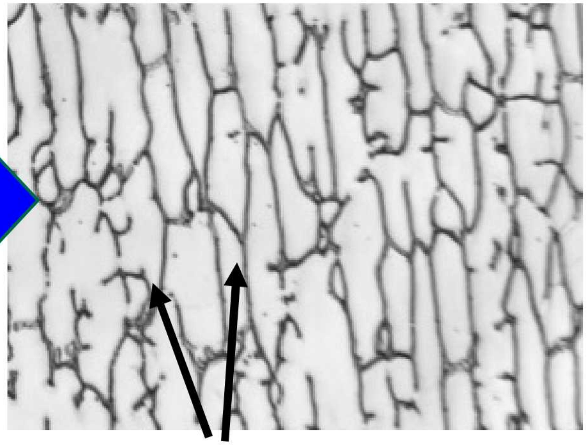
Ferrite content in Austenitic stainless steel appears to have large effect on fracture threshold (J_H)



Weld Fracture surface



Weld microstructure



δ-ferrite (skeletal)

[4] Ronevich, 2017
[12] Nibur, 2009
[14] Somerday, 2009
[16] Jackson, 2012
[17] Morgan, 2005

Ferrite dendrites provide preferential path for cracks and results in reduced fracture resistance (J_H)

Summary

- Materials used in hydrogen applications typically have high fracture resistance → E1820 EPFM applies
  - E1820 validity criteria for dimensions is more lenient than E399
- Different coupons have been shown to yield similar fracture resistance (J_H) values allowing more flexibility on specimen removal of welds and HAZ
- Techniques such as DCPD can be very helpful in identifying crack initiation and tracking crack growth
- Analysis to generate J-R curves is very involved and requires numerical integration
- Fracture resistance of austenitic stainless steels and ferritic steels is reduced in hydrogen but doesn't mean they can't be used for hydrogen infrastructure.